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PULMONARY RESERVE AND ITS INFLUENCE ON THE DEVELOPMENT OF LUNG SURGERY

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MEMBERS of the American Association for Thoracic Surgery and Guests: I wish to begin this discussion by expressing my deep appreciation for the high honor of being chosen to serve as President of our Association. I first attended a meeting of this distinguished Society in 1929. The meeting was held at Barnes Hospital, St. Louis, in a medium-sized classroom. During the 31 intervening years, thoracic and cardiovascular surgery has grown and matured, and our organization has continued to enjoy an enviable reputation among graduate medical educational groups.

During my 25 years of membership, I have attended all annual meetings except one, at which time I was doing graduate work under Prof. Ferdinand Sauerbruch at the University of Berlin. My experiences during these years, in listening to the presentations, in occasional participation in the programs, and in enjoying the general fellowship of this Association, are among the most treasured memories of my professional career.

I would like at this time also to express my appreciation to the other officers and councilors of the Association for their valued counsel, and especially to thank our Secretary, Dr. Langston, and our Administrative Assistant, Miss Hanvey, who have handled the many and varied affairs of our Society in a most expert and proficient manner.

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In deciding upon a subject for this occasion, various educational, historical, and scientific problems presented themselves. Provocative questions were not lacking in any of these areas. The subject I have chosen is one that first interested me over two decades ago at the time of several deaths following total pneumonectomy. Autopsy findings in these cases were those of cardiac failure, although no primary cardiac lesion was found. At that time, total pneumonectomy was the only curative type of surgery considered for primary carcinoma of the lung.

Although much concern regarding pulmonary function and reserve was expressed in early medical history, the full significance of this matter was not appreciated until the years of development of modern thoracic surgery. The delay in an understanding of this problem was due partly to the difficulty in

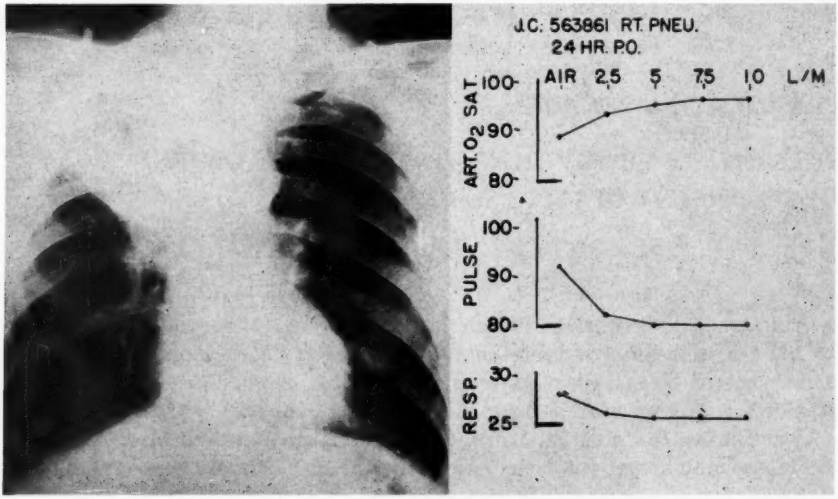


Fig. 1.—Roentgenogram of chest of a 63-year-old white man and data showing degree of desaturation of blood oxygen 24 hours following a right pneumonectomy. A satisfactory rise in arterial oxygen saturation was obtained by the administration of only 2½ L. per minute of oxygen flow via an oropharyngeal catheter. Note changes in pulse and respiration closely following the changes in arterial oxygen saturation.

evaluating pulmonary reserve, which later was forced upon us (partly by trial and error) with the evolution of modern pulmonary surgery. It is now appreciated that this problem is not confined only to pulmonary resection, but also to other intrathoracic surgery, as well as in the general field of surgery, especially in the elderly or poor-risk patient. Interference with pulmonary ventilation following a general anesthetic and major operation in the older age group, or in the obese patient, tends to encourage the retention of bronchial secretions with resultant patchy atelectasis. This in turn may lead to increased pulmonary vascular resistance, as well as to hypoxia, which results in increased strain on the right heart. Evidence that this occurs quite frequently was demonstrated repeatedly in a study of a series of 50 patients who had undergone major surgery. The average level of arterial blood oxygen on the first

day after operation was 88 per cent as seen in Fig. 1, with a range of 80 to 92 per cent. This could be readily corrected by the use of small amounts of oxygen administered through an oropharyngeal catheter. As little as 1 to 2 L. of oxygen flow per minute usually led to a desirable level of blood arterial oxygen. In the series of patients studied, some degree of hypoxia of clinical significance usually persisted for several days after surgery, the amount gradually decreasing as the patient became more active.[1]

The dangers accompanying decreased pulmonary reserve were recognized by the ancient Greeks. However, they understood relatively little of the underlying principles upon which this danger was based. As early as the 16th century, some knowledge of the influence of altered intrathoracic pressures on cardiorespiratory function was gained from animal experimentation.

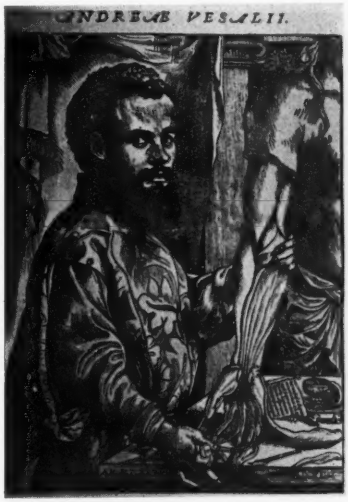


Fig. 2.—Andreas Vesalius (1514-1564), famous anatomist at the University of Padua, and one of the first medical scientists.

Andreas Vesalius,[2] a Belgian by birth and a noted anatomist and physician at the University of Padua, was one of the most outstanding figures in European medicine between Galen and Harvey (Fig. 2). Vesalius was an astute observer, an accurate recorder, and an inspiring teacher as indicated by his demonstration of altered respiratory function by animal experimentation, much as it is being done today, four centuries later. Allow me to refresh your memory on his erudite discussion with his students of the dangers of open pneumothorax during experiments on rabbits. After exposing the transparent parietal pleura through which the movements of the lung could be seen, he showed how the lung would fall away from the side of the chest wall on breaking the pleura and allowing the pleural cavity to communicate with the outside. If only one side of the chest was involved, the motion of the chest remained unchanged. However, if the opposite pleural cavity was opened, "the lungs are seen as the result of perforation to fall together and collapse.

The cardiac motion may not be observed for long, since suffocation of the animal will come on account of the collapse of the lungs. In order to restore the life of the animal, an opening is made in the upper part of the trachea, into which a pipe made from a reed is introduced. When it is breathed into, if the lung rises up, the animal receives air. The lung should be inflated to the degree to which it occupied the thorax in life. The heart now gathers strength and its motion will change beautifully. Therefore, by maintaining repeated inflation of the lung, you may have opportunity to examine the motion of the heart both by touch and sight as much as you desire.'' Thus, it is quite obvious that this great anatomist and scientist fully understood the ill effects of reduced pulmonary reserve. It is also obvious from his description of the experiment that a means of avoiding these untoward results, or of overcoming them once

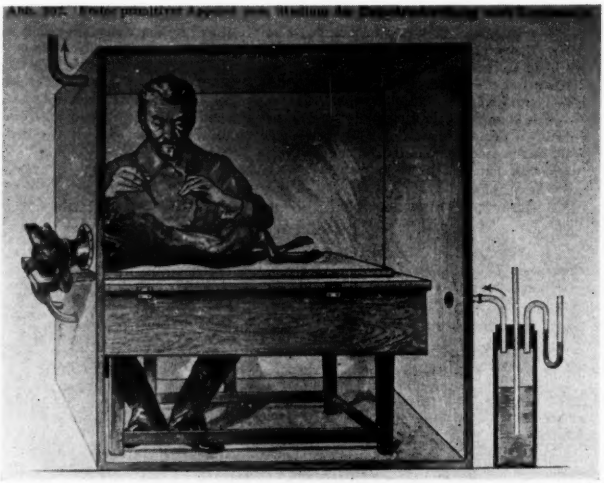


Fig. 3.—Negative pressure room developed by Sauerbruch for intrathoracic operations on animals. A similar room was constructed for clinical use (after Sauerbruch).

they were established, was possible through the use of positive pressure intratracheal insufflation. It seems incredible that the dangers associated with open pneumothorax continued to be remembered for four centuries, but that the principle involved in the method overcoming or obviating these hazards was forgotten, or at least was not associated with thoracic problems.

Methods, procedures, and even principles seem to have a way of being rediscovered again and again, and so it was with this medical problem. Three centuries later, in 1903, Johann von Mikulicz, the noted German surgeon at Breslau, visited William Worrell Mayo at Rochester and discussed problems involved in surgery of the esophagus. Following this visit, he set his young assistant, Ferdinand Sauerbruch, at that time a young doctor of 27 years of age, to investigate methods of making intrathoracic surgery a safe procedure, with relatively little hope that a solution could be found. As a result of Sauerbruch's work, a negative pressure chamber was constructed in which

open-chest operations could be safely performed under reduced atmospheric pressures[3, 4] (Fig. 3). When Brauer demonstrated that positive pressure insufflation of the lungs gave satisfactory results and was a far more practical arrangement, this type of anesthesia supplanted the negative pressure chamber. The work of Meltzer and Auer soon followed and, after overcoming certain inertia, led to the establishment of anesthetic methods and procedures in common use today.[5]

Although resection of an entire lung had been accomplished in animals as early as 1492 by Rolandus,[6] it did not become an established clinical procedure until in the early 30's when reports of a total pneumonectomy were made independently by Haight,[7] Nissen,[8] and Graham.[9] Two main factors repsonsible for the long delay in this field of surgery were (1) a lack of complete understanding of altered respiratory physiology during an open pneumothorax, and (2) the delayed development of anesthetic methods and techniques presently used in this field. Thus, in spite of observations made by Vesalius in the 16th century, almost four centuries elapsed before clinical use was made of this information.

With the operative risk associated with pulmonary resection reduced to an acceptable status, this field of surgery was extended to include resections of parts of both lungs usually performed for bilateral bronchiectasis. Eloesser[10] in 1933 was the first to report such a case, followed by Overholt[11] in 1937 with a report of a tri-lobectomy. In 1940, Graham[12] posed the question, "With how little lung tissue is life compatible?" At that time he reported the results of surgery in a patient in whom both lower and middle lobes were resected, the lingula on the left being considered as a left middle lobe, with only the two upper lobes remaining. Pulmonary resection was extended even farther in this patient, in whom, in addition to the four lower lobes, a portion of the right upper lobe was also excised for emphysematous blebs and bullae which had developed in association with bilateral bronchiectasis (Fig. 4). Reimann[13] and his co-workers have demonstrated on dogs that overdistention of the remaining lung tissue following massive reduction of lung capacity, such as by total pneumonectomy, is not accompanied by any significant increase in pulmonary resistance. Even with reduction of lung capacity to one upper lobe or 15 per cent of the normal, pulmonary artery pressures were no greater in the overdistended state than in the normally expanded state of the remaining lung tissue. These results corroborate those of Charbon and Adams[14] who found that filling of a pleural space with a plastic prosthesis following pneumonectomy did not improve the survival rate following further reduction of lung capacity to 15 per cent. Instead, he obtained no survivors at all in a group of 12 dogs, whereas, when no prosthesis was used, 4 of 13 dogs survived for weeks or months following operation. Graham's posed question was a very pertinent one and required further investigation in the laboratory. In experiments on dogs, reported by Phillips[15] and Rasmussen[16] and their associates, pulmonary capacity was reduced successfully to the right

upper lobe or approximately 15 per cent of the original lung capacity. To accomplish this, it was necessary to reduce lung capacity in stages extended over a period of several weeks. This was accomplished by a combination of resection of the lower lobes as the first stage, and later occlusion of the bronchi to the remainder of the lung with the exception of an upper lobe, and subsequent

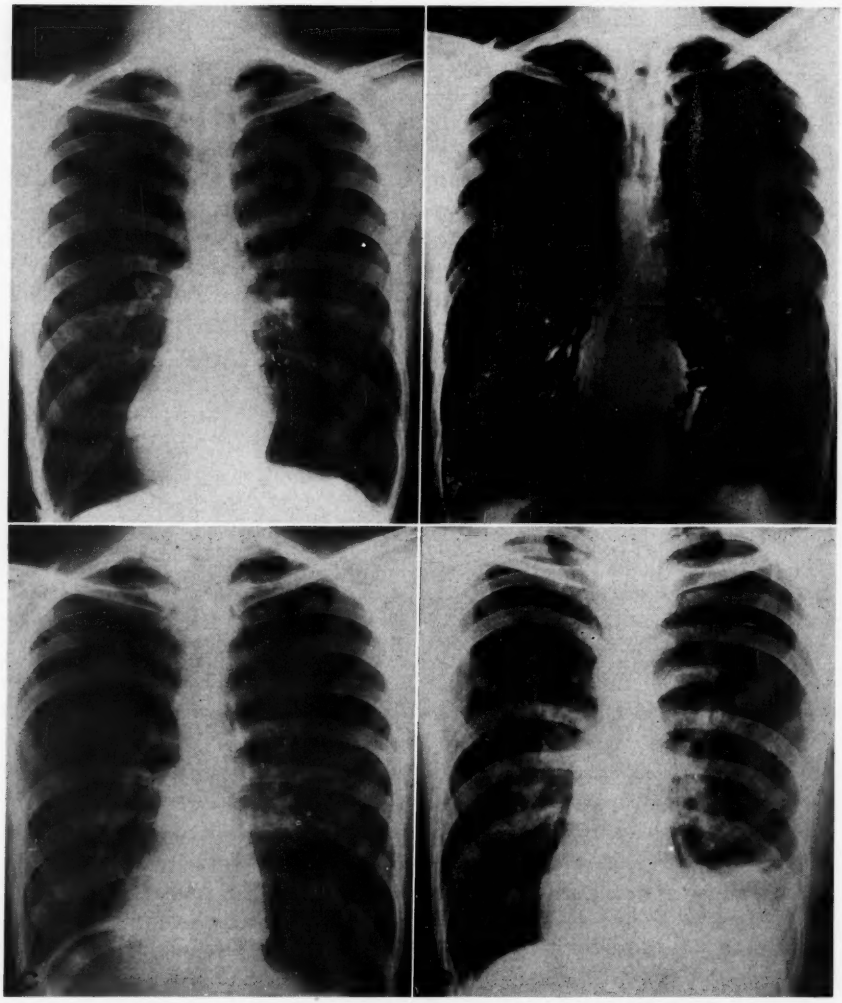


Fig. 4.—Roentgenograms of chest of a 33-year-old white man which show *(A)* normal posteroanterior view of chest exhibiting bilateral emphysema in the lower lung fields; *(B)* bronchogram showing bronchiectasis with complete collapse of both lower lobes and the right middle lobe, as well as involvement of the left upper lobe; and *(C)* and *(D)* x-ray appearance after resection of both lower lobes, the right middle lobe, as well as the lower portion of the right upper lobe for bullous emphysema, and resection of the lingula of the left upper lobe (patient's pulmonary reserve reduction was due to infection gradually over a period of years; compensation was adequate to obviate serious cardiopulmonary symptoms following bilateral resection).

collapse of those lobes by absorption of the entrapped air. Carlson and his co-workers,[17] at a later date, were able to accomplish this marked reduction in capacity to 15 per cent by a staged resection of the remaining portion of the lung. However, only 4 of 13 animals survived this method; the remainder died of excessive (right) heart strain (pulmonary artery pressures were increased by 100+ per cent). Thus, the dog's ability to tolerate marked reduction of lung capacity was governed, at least in part, by the rate at which the diminution was made. Furthermore, when a small physiologic shunt remained, such as that represented by the remaining atelectatic lobes, the risk of reducing the capacity to this small amount was lessened (Fig. 5, *A*).

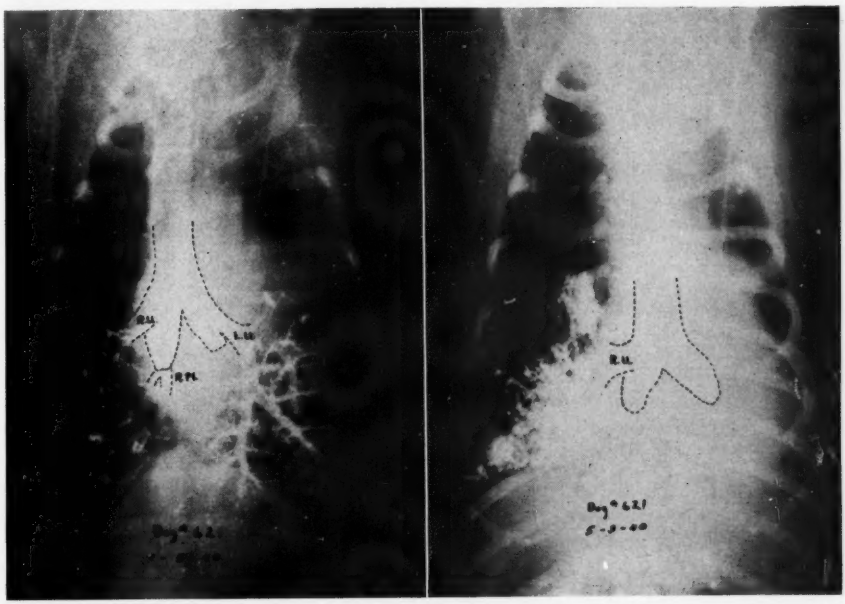


Fig. 5*A*.—Two bronchograms of a dog made after a staged reduction in lung capacity by a combination of surgery and bronchial stenosis. On the left, the capacity has been reduced to both upper lobes and the right middle lobe or approximately 38.7 per cent of normal through bilateral excision of both lower and the right accessory lobes. On the right, the capacity has been further reduced to only the right upper lung lobe or approximately 15 per cent of normal through bronchial stenosis of the right middle and the left upper lobes. By staging the reduction of lung capacity slowly, this animal was able to tolerate reduction to only this small per cent. (From Rasmussen et al.[16])

Following this marked reduction in capacity, these animals appeared to be healthy, remained well nourished, and were able to tolerate moderate exercise. They were usually active in the kennel and, although somewhat dyspneic on exercise, did not show evidence of cyanosis. Upon sacrificing such an animal having only 15 per cent of his original lung capacity, the remaining lobe was found greatly overdistended and, on microscopic examination, revealed some fragmentation of the peripheral respiratory units (Fig. 5, *B*). This, however, did not represent a true emphysema since no increase in fibrous tissue in the alveolar walls was observed. In spite of this marked alteration

of microscopic appearance, these animals tolerated a rarefied atmosphere remarkably well. A test of their tolerance to such a situation was made by placing them in an evacuation chamber and reducing the pressure therein until consciousness was lost. When normal dogs were subjected to this procedure they were able to tolerate a reduction in pressure to approximately 221.6 mm. Hg (comparable to an altitude of 30,400 feet and 6.25 per cent O_2), or a pressure similar to that tolerated by man before losing consciousness. Dogs with only three functioning lung lobes, or approximately 38 per cent of normal, had the same tolerance. When the one-lobe dogs (15 per cent of normal) were

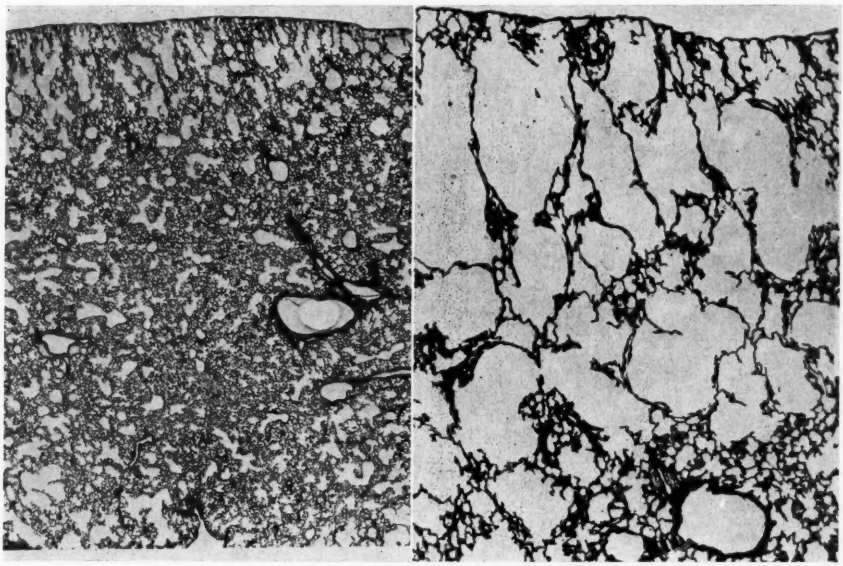


Fig. 5*B*.—Microscopic appearance of a dog's lung following reduction in pulmonary capacity to one upper lobe or 15 per cent of normal. Note marked tendency to overdistention of terminal respiratory units, especially at the peripheral portion of the lung, with marked dilatation of terminal respiratory units. Definite compensatory emphysematous changes are seen in the alveolar ducts and sacs; however, no increased fibrous tissue production is present. (*Left*, ×7—*Right*, ×20; both reduced ⅔.) (From Rasmussen.[16])

subjected to this test, consciousness was lost at 270 mm. Hg (altitude of 25,833 feet and only 7.75 per cent O_2), thus demonstrating a remarkable ability to oxygenate the blood with but a small amount of functioning lung tissue (Table I). Although these animals appeared well for a few weeks or months following these experiments, most of them died much earlier than would have been otherwise expected. At the time these experiments were made, the mechanism of death was not well understood.

The ability of human beings to tolerate marked reduction in pulmonary capacity has been repeatedly demonstrated by the use of bilateral pneumothorax in the treatment of pulmonary tuberculosis. Here again it was necessary gradually to produce collapse in order to avoid cardiopulmonary distress. An example of this marked reduction in capacity tolerance is illustrated by a

TABLE I. RESPIRATORY RESERVE AT REST AS DETERMINED BY REDUCTION OF ATMOSPHERIC PRESSURE

STANDARD ATMOSPHERIC PRESSURE		CONDITION OF ANIMAL AND % OF FUNCTIONING LUNG	NO. OF DOG	ALTITUDE TOLERATED	TIME OF ASCENT MINUTES	AVERAGES	
ALTITUDE FEET	PRESSURE MM. Hg					ALTITUDE FEET	PRESSURE MM. Hg
0	760		1	30,500	10		
			2	30,500	10		
1,000	733	Normal (6 lobes) 100%	3	29,500	10	30,400	221.6
5,000	632.4		4	32,000	8		
10,000	522.6		4	29,500	11		
15,000	428.8		917	32,000	6		
			993	32,000	7		
20,000	349.2	3 lobes 38%	3	25,000	7	30,000	225.6
25,000	282		637	31,000	9		
			871	30,000	9		
30,000	225.6						
		2 lobes	636	27,500	4	26,000	269.8
35,000	178.7	23%	869	24,500	6		
40,000	140.7						
			635	26,500*	5		
		1 lobe	621	25,000†	6	25,833	272
		15%	695	26,000	10		

Table shows respiratory reserve at rest during the lowering of pressure in an evacuation chamber in dogs with normal lung capacity as well as with reduced lung capacity to 38, 23, and 15 per cent of normal. Note marked degree of tolerance to rarefied atmosphere with lower oxygen available to animals with only 15 per cent of original capacity. The percentage of oxygen available at 30,000 feet altitude or 230 mm. Hg pressure is approximately 6.4 per cent, whereas that available at 26,000 feet altitude or a pressure of 270 mm. Hg is approximately 7.7 per cent. (From Rasmussen et al.[16])

*Failed to recover.

†Did not become unconscious.

patient treated by Dr. Victor S. Randolph. A roentgenogram of this patient taken at the end of deep expiration showed scarcely any inflated lung tissue. The second view taken at the end of deep inspiration revealed relatively little functioning lung on either side (Fig. 6). During this phase of the patient's treatment, he was at bed rest and therefore the requirements for oxygen were considerably reduced. (This was a young adult male patient and therefore the lung tissue might be expected to tolerate a greater degree of collapse than in an older individual.)

From the evidence these patients revealed and the results of animal experimentation, it appeared that total pneumonectomy was a procedure that should be well tolerated with little risk to the patient. In normal, healthy animals, this has been proved beyond a doubt. Likewise, in the younger individuals, cardiopulmonary function has been repeatedly demonstrated to be quite adequate, not only while at rest, but also sufficient to insure a relatively normal way of life.

However, as more experience in this problem was obtained, the mortality rate of this operation in older people (above 60 years of age) was found to be definitely increased. Furthermore, the cause of death in some patients was inadequately explained by the results of pulmonary function studies prior to surgery. This led to further investigation of the problem on dogs, in which pulmonary resistance and pulmonary flow rates were correlated with pulmonary function values before and after varying degrees of reduction in lung capacity.[18]

It was fully appreciated that in animals only relatively normal lung tissue was involved, whereas in clinical cases, dealing with inflammatory, neoplastic, or degenerative disease, a combination of changes in lung tissue structure, as well as function, might very well play an important role. These experiments revealed that when a dog's lung capacity was rapidly reduced to 15 or 20 per cent of normal, pulmonary vascular resistance was more than doubled, and that an intolerable level of pulmonary hypertension occurred in a high percentage of animals. Furthermore, it was found that a demand for increased cardiac output during exercise further increased the degree of cardiac strain.

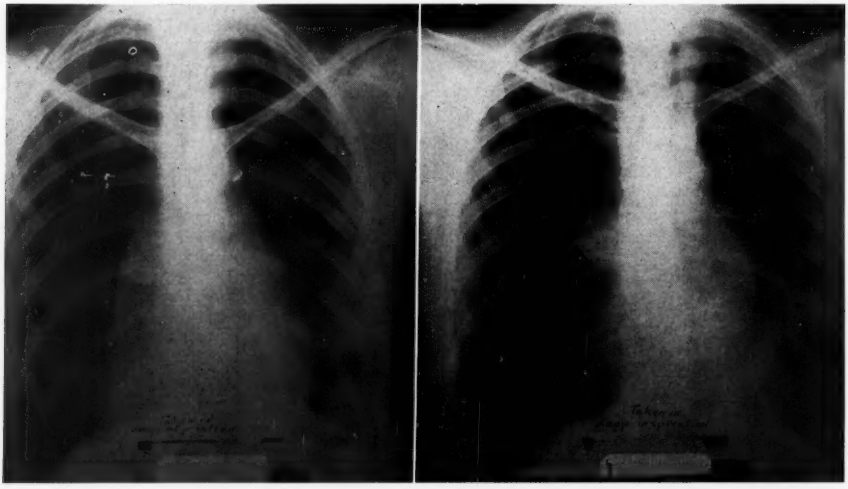


Fig. 6.—Two roentgenograms of the chest of a young, white man taken during deep expiration on left and on deep inspiration on right. This patient was being treated for bilateral pulmonary tuberculosis by bilateral pneumothorax. Note marked degree of collapse of both lungs by therapy. Since the requirements for oxygen at rest were quite low and since this was a relatively young individual, this marked degree of reduction in lung capacity was tolerated.

On the other hand, blood oxygen saturation suffered relatively little (5 per cent) while the animal was at rest, even with reduction of lung capacity from 50 to 15 per cent. During exercise, the saturation level dropped precipitously but could be restored to normal immediately by the administration of oxygen (Fig. 7).

In patients with bilateral alteration of the lung which is due to inflammatory, degenerative or other conditions, the pulmonary vascular resistance may be increased by as much as 100 per cent. This is especially true in the so-called older age group. Thus, removal of an entire lung may carry considerable risk. In nonmalignant disease it is frequently possible to limit pulmonary resection, thus preserving maximum lung capacity. However, in the case of malignant lesions, it has been generally believed that removal of the entire lung along with adjacent tumor-bearing tissue is the operation of choice, when it can be tolerated by the patient. In patients of this older age group with an already reduced pulmonary reserve, a sudden additional reduction in lung capacity by pneumonectomy may lead to an intolerable degree

of increased cardiac strain due to increased pulmonary vascular resistance without lowering blood oxygenation to a dangerous level. Postoperative alteration in pulmonary tissue and chest wall function may well augment the serious degree of increased pulmonary vascular resistance produced by pulmonary resection. Since the risk of pneumonectomy is increased in the older age group having poor pulmonary reserve, repeated attempts have been made to determine the "resection tolerance" of such patients prior to surgery. Studies made by a number of investigators[19] have increased our knowledge of factors concerned with this problem. In the past several years, special attention has been given to the problem of changes in pulmonary vascular resistance attending the resection of lung tissue both in animals and in man.[20]

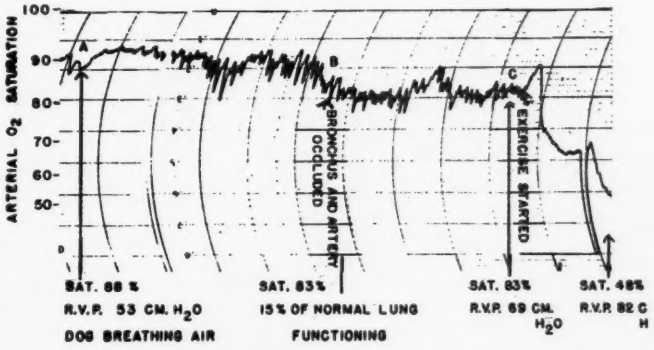


Fig. 7.—Dog 737—March 25, 1952. Continuous recording oximeter tracing of oxygen saturation in the dog during reduction in pulmonary capacity from 50 per cent on the left to 15 per cent by suddenly obstructing the bronchus and vessels to all except one upper lobe at point *B*. Saturation levels, right ventricular pressures and other data are indicated below the tracing. The record reveals a marked elevation in right ventricular pressure from 53 to 69 cm. of water with reduction in lung capacity from 50 per cent at *A* to 15 per cent at *B* and *C*. Oxygen saturation during this period was reduced by only 5 per cent. The effect of exercise begun at *C* on oxygen saturation as well as right ventricular pressure is demonstrated. When oxygen was given by nasal catheter, the saturation level became suddenly elevated to normal; however, right ventricular pressures remained high. (From Adams et al.[18])

In young, healthy people, both pulmonary function studies as well as pulmonary vascular data show a considerable range of safety in the majority of cases following total pneumonectomy. Blood oxygen saturation is usually normal during the resting state and shows only mild elevation during exercise. The cardiac output is likewise normal at rest, and increases in a normal manner with exercise. The following patients will serve as examples of fairly characteristic responses following pneumonectomy in older people. The fatalities which occurred in Cases 1 and 2 were due to intolerable pulmonary hypertension and cardiac failure, occurring 19 and 11 days, respectively, following pneumonectomy for malignant disease.

CASE 1.—The first patient (O. C., Case 1) was a 66-year-old white man whose pulmonary function studies made before operation showed a moderate reduction of ventilatory capacity. At the time of surgery, preocclusion pressure of the pumonary artery showed a mean of 39 cm. of water. This pressure rose to 53 cm. of water after occlusion of this artery. The surgical procedure was tolerated quite well and his immediate postoperative course was

quite satisfactory. Oximetric studies revealed decreased saturation of blood oxygen; however, this was easily corrected with a very low flow of oxygen via oropharyngeal catheter. Although the patient was digitalized, his condition did not improve and he died on the nineteenth postoperative day of cardiorespiratory failure (Fig. 8).

CASE 2.—The second patient (R. R., Case 2) was a 59-year-old white man who underwent a total pneumonectomy for primary carcinoma of the left lung involving the left chest wall. The general physical examination of this patient showed him to be in relatively good condition prior to surgery. Likewise, pulmonary function studies revealed only mild to moderate reduction in functional values. During operation, preocclusion pressures were

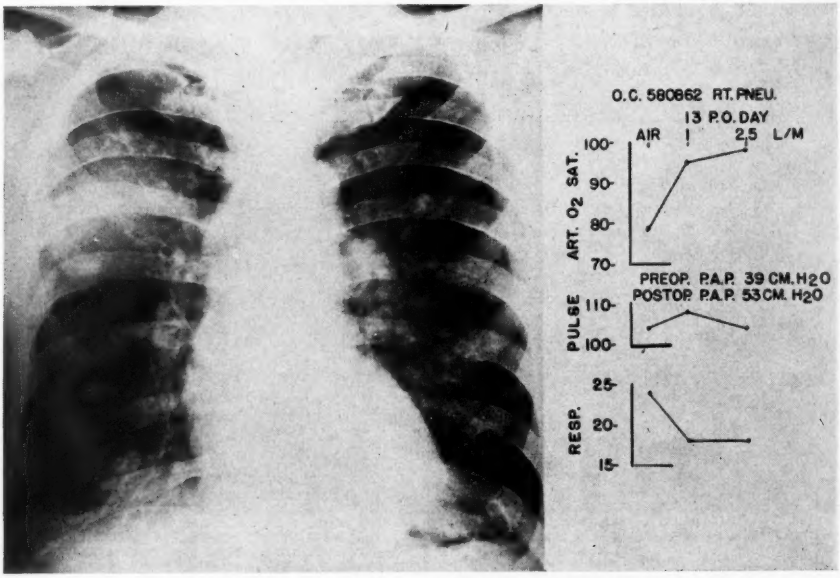


Fig. 8.—Case 1 (O. C.). Roentgenogram of the chest which reveals a bronchogenic carcinoma of the right lung. Data on *right* were obtained 13 days following surgery, except for preocclusion and postocclusion pressures of pulmonary artery at the time of surgery. Note lower oxygen saturation to 80 per cent which was elevated to a satisfactory level with only 1 L. per minute of oxygen flow via an oropharyngeal catheter. Death occurred on the ninteenth day after operation of cardiac failure.

48/12 mm. Hg. Following occlusion, the pressures rose to 60/12 mm. Hg. Because of this high pulmonary resistance, he was started on prophylactic digitalis. He appeared to be progressing satisfactorily, although the electrocardiogram revealed some premature auricular beats. His convalescence on the fifth postoperative day was quite satisfactory, the blood oxygen saturation being 93 per cent on air with an elevation to 98 per cent on oxygen. X-ray studies showed a satisfactory postoperative appearance of the chest. By the ninth postoperative day, he became rather lethargic and again showed evidence of auricular fibrillation. The oxygen saturation studies still remained good, being 95 per cent on air and 100 per cent on oxygen on the tenth day. On the following day, he suddenly became quite dyspneic and died (Fig. 9).

CASE 3.—This next case is presented to indicate how data from pulmonary function studies appeared unsatisfactory, whereas those obtained from investigation of pulmonary circulation proved to be quite adequate, and where the results of surgery were satisfactory. This patient was a 63-year-old white man (H. M., Case 3) who had had a pneumonectomy

for a primary carcinoma of the left lung. Pulmonary function studies showed relatively normal ventilatory values, but an increased residual volume and a markedly decreased maximum mid-expiratory flow, and timed vital capacity was definitely below normal. Circulatory studies on this patient showed a normal pulmonary artery pressure both at rest and during exercise before operation. Likewise, arterial oxygen saturation was within satisfactory limits. Pulmonary vascular resistance decreased during exercise while cardiac output increased. This patient underwent a left pneumonectomy without difficulty. The mean pulmonary artery pressures have remained about the same during the 4-month period of study since operation. The pulmonary vascular resistance has continued low and has permitted an adequate increase in cardiac output without the necessity of increased pulmonary artery tension.

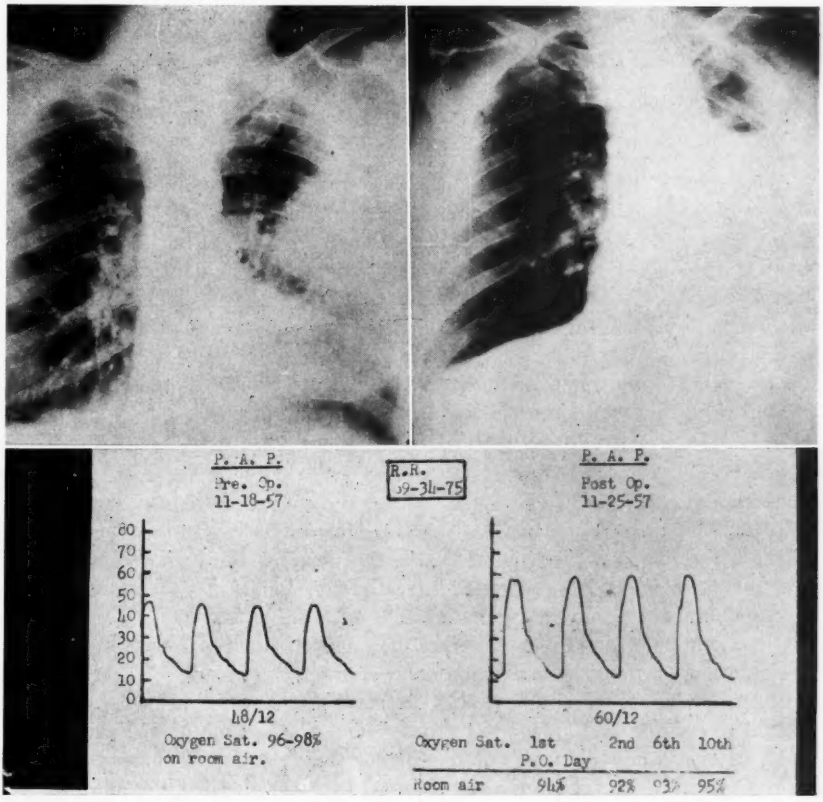


Fig. 9.—Case 2 (R. R.). Roentgenograms of the chest made before and following a left pneumonectomy. Preocclusion pressures were 48/12 and postocclusion 60/12 mm. Hg. Oxygen saturation levels were quite satisfactory both before and following surgery. The patient died on the eleventh day after operation of cardiac failure.

Case 4.—This next patient demonstrated opposite results during study before operation, that is, the results of pulmonary function studies were excellent in all respects and tended to indicate that the operation would carry little risk. He was a 61-year-old white man (J. D., Case 4) in whom a pneumonectomy for primary carcinoma of the right lung was done. At surgery, the preocclusion pressure in the pulmonary artery was found to be

double the normal value. After occluding the artery to the side to be removed, this pressure increased 10 to 15 per cent. Because of the location of the tumor, it was necessary to do a total pneumonectomy. In view of this patient's marked pulmonary resistance and pulmonary hypertension, all precautions were taken to bring him through the postoperative period. This included a tracheostomy, oxygen therapy, absolute bed rest, and digitalization of the heart. He responded in a satisfactory manner and was kept on this routine for 4 weeks. At this time, a study of his lesser circulatory values revealed approximately the same findings as at the time of operation. Mild exercise increased these pressures materially. Repeated tests made at 2 and 4 months after surgery showed a gradually decreasing level of pulmonary artery pressures with relatively normal blood oxygen saturation. However, as the pulmonary artery pressures were reduced in amount, the cardiac output was likewise reduced, indicating a remaining high pulmonary resistance. This patient was allowed to go home 6 weeks after operation and was readmitted for these studies. Shortly after returning home on the last occasion, he suddenly died. He had been receiving x-ray therapy for metastases and it was felt that spread of the tumor may have played a role in the gradually diminishing cardiac function.

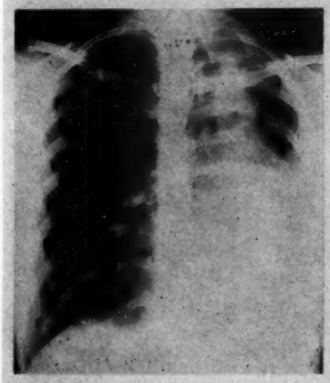
CHRONIC PULMONARY HYPERTENSION

After patients have survived the ablation of an entire lung, the question might be raised, "How well will this reduced pulmonary capacity be tolerated during later life?" Should the patient change his occupation if it requires strenuous exercise or work and lead a more sedentary type of life? What may be anticipated in the way of life expectancy? It is well known that some patients may continue their normal occupation for many years without difficulty. On the other hand, either shortly after operation or at some period of years later, so-called "pulmonary cripples" have developed with complete incapacitation and reduction of the normal life span.

In order to answer some of these questions, a study was begun some 10 years ago and accelerated during the past 3 years with financial aid from the American Cancer Society. This has enabled the collection of considerable data on 55 patients whose operation had been performed up to 16 years before the study. These patients were admitted to the hospital for a period of 2 or 3 days during which time a detailed investigation included (1) securing data for clinical evaluation, (2) measurements of various aspects of pulmonary function, and (3) obtaining pressure flow values of the lesser circulation. A correlation of the results from each evaluation was made. These detailed studies extended from a few weeks to several years following surgery, in addition to studies made prior to operation and at the time of operation. The results of this study to date would indicate that in general the younger age group of patients, namely, under 50 years of age, revealed little or no difficulty in either pulmonary or vascular reserve during the several years after operation. Functional studies showed some decrease in ventilatory capacity; however, diffusion ability remained normal and adequate, permitting reasonable degrees of exercise or work. Likewise, pulmonary-circulatory studies showed normal resting pressure flow values with only moderate elevation of pressure on exercise (Fig. 10—J. K., Case 5). Some of these patients have been followed over a period of 4 or 5 years, and the pulmonary and circulatory determinations have remained approximately constant. On the other hand, some patients under

the age of 50 remained healthy and active for a period of 5 to 10 years at which time they began to develop symptoms of cardiopulmonary insufficiency when active, and subsequently became decompensated, as indicated by the following example.

CASE 6.—This patient was a 56-year-old white man (O. L., Case 6), who, 11 years previously at the age of 45, had had a right pneumonectomy for bronchogenic carcinoma of the lung. After operation, he had an uneventful convalescence and was followed in the Out-patient Department. Eight years following pneumonectomy he began showing signs of increasing pulmonary insufficiency with marked dyspnea, orthopnea, and chronic



J.K. 37 F.
3 yrs. post-left pneumonectomy

FUNCTIONAL CLASS I.

T.L.C.	3.85 L.	
V.C.	2.05 L. (68%)	
R.V.	1.5 L.	
M.B.C.	57.0 L./min. (60%)	
1 sec V.C.	74%	
	Rest	Exer.
Pulm. Art. Press.	$\frac{25}{8}$ (14)	$\frac{41}{17}$ (25)
Art. O_2 Sat.	95%	97%
Pulse Rate	110.0	146.0
O_2 Consumption	235.0	579.0
Cardiac Output (L./min.)	5.5	9.3

Fig. 10.—Case 5 (J. K.). Roentgenogram of chest and data collected from cardiopulmonary evaluation on a 37-year-old white woman 3 years after a left pneumonectomy. Note relatively good pulmonary function values, satisfactory arterial oxygen saturation levels at rest and during exercise, normal cardiac output response to exercise with only moderate increase in pulmonary artery pressure as compared to that of the resting state which is at a normal level. *T.C.L.* = total lung capacity; *V.C.* = vital capacity—per cent of normal predicted for subject with two lungs; *R.V.* = residual volume; *M.B.C.* = maximum breathing capacity—per cent of predicted value for a normal chest with both lungs; 1 sec. V.C. = per cent of the vital capacity expired in the first second; *Pulm. Art. Press.* = pulmonary artery pressures (mm. Hg) (mean pulmonary artery pressure in parentheses); *Art. O_2 Sat.* = arterial oxygen saturation; *O_2 Consumption* = oxygen consumption (ml./min.). (From Harrison et al.[29])

nonproductive cough. On the early morning of admission, he awakened and coughed up two or three tablespoons of bright red blood. General physical examination showed nothing remarkably abnormal. However, cardiopulmonary function evaluation revealed lowered ventilatory values, blood-oxygen saturation of 90 per cent, and a right ventricular pressure of 56/0 mm. Hg. A moderate degree of exercise for one minute lowered the saturation to 86 per cent and elevated the right ventricular pressure to 85/0 mm. Hg. This patient's condition has continued to worsen and he is at the present time a pulmonary cripple, being unable to tolerate more than walking across the room.

In still other patients, cardiopulmonary insufficiency appeared and was markedly accentuated during mild upper respiratory infections. The following case illustrates this point.

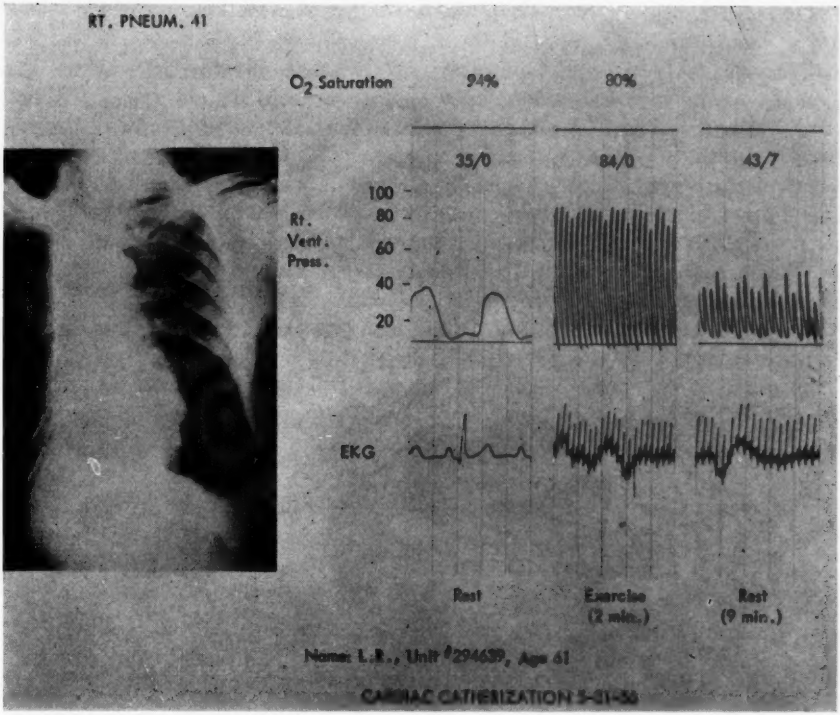
CASE 7.—This patient was a 61-year-old white man (L. R., Case 7) who had had a right pneumonectomy for bronchogenic carcinoma 13½ years previously at the age of 47.

Two years later, an empyema developed in the right chest for which a Schede thoracoplasty was made. For 10 years following pneumonectomy he was able to do full-time office work without any evidence of a cardiopulmonary problem. At the end of that time, there developed one-flight exertional dyspnea and a mild nonproductive cough. Physical examination showed signs of mild decompensation. He had had a mild upper respiratory infection prior to admission which had accentuated his dyspnea. Pulmonary function studies showed relatively normal values, except for a low maximum breathing capacity. His oxygen saturation at rest was 94 per cent. Cardiac catheterization showed a pressure of 35/0 mm. Hg. With only moderate exercise, his pressures elevated to 84/0 mm. Hg and the saturation was lowered to 80 per cent of normal. With the subsidence of his upper respiratory infection, his symptoms became much relieved and he continued his routine work. When the cardiopulmonary studies were repeated 2 years later, 15½ years following pneumonectomy, the pulmonary function values were somewhat diminished and arterial oxygen saturation was 94 per cent. Pulmonary artery pressure at this time was only mildly elevated but became almost doubled in amount on moderate exercise. The oxygen saturation, however, was not lowered by exercise. This patient has subsequently become gradually less able to carry on his work without difficulty. Although not a pulmonary cripple at the present time, he has had to reduce his activities and lead a very sedentary type of life (Fig. 11, *A* and *B*).

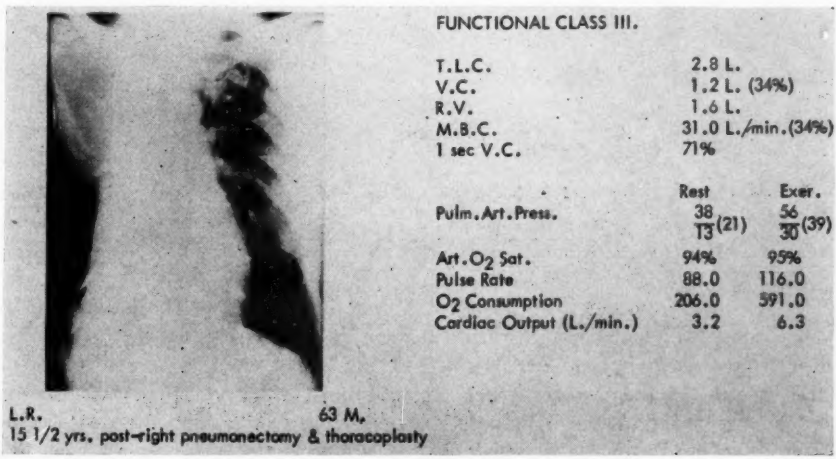
In older patients who underwent surgery after the age of 60, acute or chronic pulmonary hypertension was more likely to develop than in patients under 50 years of age. Although our clinical data are as yet insufficient percentagewise for prognostication, patients over 60 years of age are more likely to develop pulmonary hypertension sooner than are those patients whose surgery was performed before 50 years of age. This would suggest that if surgery is performed in the younger age group, a degree of compensation may occur over a period of years following surgery which will offset the development of chronic pulmonary hypertension. The following case is an illustration of this point.

CASE 8.—This patient was a white man, 66 years of age at the time of pneumonectomy (J. S., Case 8), whose convalescence after operation was quite satisfactory. Within 5 years following operation, he began showing an increasing amount of dyspnea on mild exertion. Eight years later, he was having much more difficulty and was admitted for study. Pulmonary function data indicated a moderate to severe degree of reduction in maximum breathing capacity and timed vital capacity. In spite of this, the oxygen saturation was 96 per cent. Pulmonary artery pressures at rest were markedly elevated to 75/35 with a mean of 48 mm. Hg. On moderate exercise, this rose to 112/45 with a mean of 67, at which time the oxygen saturation had dropped to 90 per cent. He was put on digitalis and reduced activity with considerable relief of symptoms. However, in spite of this regimen, his degree of incapacitation continued to increase. He died suddenly of cardiac decompensations, having been a pulmonary cripple during the preceding 4 or 5 years (Fig. 12).

This study has led us to believe that a number of things may be considered when accurate determinations of the pulmonary and circulatory status are made prior to, or at the time of, surgery for pulmonary abnormalities. In the case of nonmalignant pulmonary lesions, added precautions may be taken to insure adequate cardiopulmonary reserve following surgery. In some conditions, a preoperative period of medical management may alter the pulmonary lesion to such an extent that cardiopulmonary reserve may be enhanced and



A.



B.

Fig. 11.—Case 7 (L. R.). *A*, Roentgenogram of chest and data obtained on cardiopulmonary evaluation 13½ years after a right pneumonectomy; *B*, the same information obtained 2 years later, namely, 15½ years postpneumonectomy. The data obtained in *A* were shortly after an upper respiratory infection which had led to some degree of cardiac decompensation. Note a lowering of pulmonary function values as well as an increased amount of lesser circulatory pressure at the time of this patient's infection as compared to that obtained after the infection had subsided. (Same key as in Fig. 10.) (*B*, From Harrison et al.[20])

surgery made less hazardous. In a case of neoplastic disease in which the lesion is peripherally located and reserve appears to be limited, removal of less than an entire lung may well be adequate for ablation of all tumor-bearing tissue. Although total pneumonectomy may be the procedure of choice in most of these patients, many long-term survivals have been reported following ablation of one or two lung lobes. When it is essential to remove an entire lung in patients with low cardiopulmonary reserve, the employment of various measures for supporting the individual through surgery may insure a more satisfactory result. Since increased pulmonary resistance requires a greater right heart load with increased pulmonary pressures for the maintenance of adequate cardiac output, reduction of activity through sedentary types of employment, restriction of other physical activities, and the prevention of pulmonary infections may go far in preventing the development of a "pulmonary cripple."

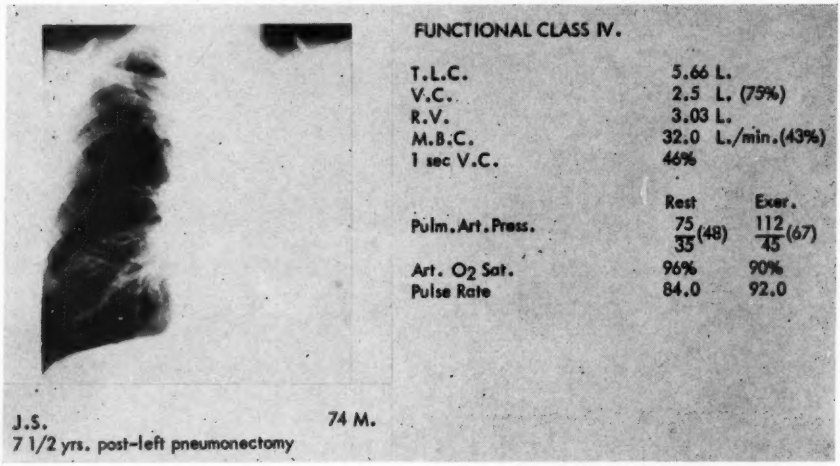


Fig. 12.—Case 8 (J. S.). Roentgenogram of chest and data collected at cardiopulmonary evaluation on a 74-year-old white man 7½ years after a left pneumonectomy. Note some lowering of pulmonary function values with, however, a normal arterial oxygen saturation during rest. The pulmonary artery pressures in this patient were extremely high and became markedly elevated with moderate exercise. (Same key as in Fig. 10.) (From Harrison et al.[20])

The modern trend in pulmonary surgery is to conserve on the amount of lung resected. Furthermore, attempts are made to re-establish functioning lung tissue when it has been disabled by disease or trauma. An example of this is seen in the use of bronchoplasty following bronchial stenosis due to pulmonary tuberculosis. Another example is the re-aeration of an atelectatic lung following traumatic stenosis of a primary bronchus. The report given this morning by Dr. Long and his co-workers was another step forward in this direction. Progress has been made in this field by several workers[21-24] who have reported a number of instances of successful re-aeration of an atelectatic lung. Studies have at times not been available by which to determine the physiologic status of these re-aerated lungs. It is hoped that in the future,

surgeons who have this opportunity may make physiologic studies which will determine if the human lung reacts in a manner similar to that of the dog's lung in a state of chronic atelectasis. Although the studies reported by Dr. Long show that a re-inflated atelectatic lung in dogs has only 25 to 30 per cent of its original functional value, nonetheless this small amount of function may mean considerable to the individual as cardiopulmonary reserve diminishes during later years. Furthermore, the functioning lung tissue would then be distributed to both sides of the tracheobronchial tree.

Time has not permitted giving credit to the many workers who have made valuable contributions in this field. This will appear in the published article. In addition, I wish to give a full measure of credit to Drs. Harrison, Long, Reimann, Benfield, Nigro, Attalla, Borquez Vial, Mikouchi, and Shankarappa, who have contributed materially in the investigative work referred to in this discussion. With the continuing increase in life expectancy, this problem in connection with lung surgery assumes an increasing importance. Much more work needs to be done and a step in this direction is replacement of a diseased lung by transplantation of a healthy one. Transplantation of liver, spleen, kidney, lung[25] and other organs has proved to be technically assured. Inroads on the problem of the tissue "rejection phenomenon" are gradually being made. With continued united effort, scientific endeavor, and imagination, what is impossible today may be an accepted procedure in the not-too-distant future.

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HONORED GUEST'S ADDRESS

NEW FINDINGS IN THE CORONARY-ENCEPHALIC PERFUSION IN DEPRESSED SURGICAL CASES

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THE great privilege of being requested to address, scientifically, this distinguished Society is an honor to me, to my country, and to my university.

I have accepted with modesty, not in the hope that my presentation may contribute much to scientific knowledge, but rather that this honor may serve as a stimulus to further experimentation and research among the young doctors of my country.

For this opportunity and recognition for my country, my colleagues, and myself, I am deeply grateful to Dr. William Adams, Dr. Langston, and the Committee that verified my nomination. Thank you.

The introduction of extracorporeal circulation and the progress attained in this field induced us more than 5 years ago to institute experiments related to the application of blood by perfusion to different parts of the body, in an effort to detect its possible therapeutic value in diverse pathologic conditions.

One of the studies which seemed to present possibilities and, therefore, has been continued in our laboratory pertains to the application of myocardial and encephalic perfusions in various acutely depressed states in which surgery is the only curative indication.

After extended animal experimentation the procedure was applied to human patients in an acutely depressed condition, due either to trauma, or to pathologic manifestations for which surgery was mandatory.

Finally, in the past year the procedure has been applied as a depression-preventive measure in surgical cases involving major risk.

This is a report of our experiences and findings to the present time in animals and human patients.

From the Department of Surgery and Surgical Investigation, University of Guadalajara Medical School, and Surgical Departments of Santa Margarita, Civil and Zoquipan Hospitals, Guadalajara, Mexico.

Honored Guest's Address: Presented at the Fortieth Annual Meeting of The American Association for Thoracic Surgery at Miami Beach, Fla., May 11-13, 1960.

EXPERIMENTAL STUDIES*

To date the experiments have been performed on 525 dogs. These animals were subjected to massive blood loss by intubation of a large artery, either the abdominal aorta or the aortic arch, using a plastic tube introduced into the femoral or subclavian artery. The animals were subjected to bleeding and the spontaneous emptying of blood through the tube. Suction was then applied through the same tube to ensure maximum blood drainage. Blood loss was determined by radioactive means employing I^{131} and iodized albumin. By this method the volume of blood lost was estimated as 90 per cent in some animals and 95 per cent in others. It is noteworthy that to obtain this volumetric loss, suction was a requisite, as the large vessels mentioned spontaneously cease flowing when the volume of blood loss is between 60 and 70 per cent.

To avoid coagulation during this and subsequent steps, all animals received an intravenous dose of heparin, 2 mg. for each kilogram of weight, before arteriotomy. The temperature of the operating theatre was kept at a constant 27° C., which is our medial yearly temperature. In an attempt to avoid extraneous factors these experimental animals were treated as nearly as possible to a normal environment. Only one group, in which the thorax was opened, was anesthetized.

These animals were subjected to the following observations and controls: direct arterial pressure by intubation, electrocardiographic and electroencephalographic tests, body temperature control, blood chemistry and gasometric studies, and control of blood volume loss by the radioactive tests just mentioned.

After obtaining the maximum blood volume loss, oxygenated and heparinized blood, 18 mg. for each 500 c.c., was transfused immediately.

In 275 dogs the blood was introduced by coronary-encephalic perfusion as the initial step, followed by intravenous infusion. In the other group of 250 dogs the blood was introduced by intravenous or intra-arterial transfusion, both under pressure. The latter animals were used as a control group.

I. *Coronary-Encephalic Perfusion* (Fig. 1).—This procedure was used in 275 animals. A Sigmamotor pump was used with the Lillehei-DeWall apparatus. Later the De Bakey pump, employing the Kay-Anderson apparatus, was used, and more recently we have constructed a simple pump, using the De Bakey system. The blood was pumped through a plastic tube which had previously been introduced through a transverse incision in one of the femoral arteries and carried to the superior third of the descending thoracic aorta.

The amount of blood in each impulse was between 100 and 400 c.c., perfused at intervals. Once a normal or almost normal blood pressure level had been obtained by means of perfusion, the injection of blood was continued intravenously in the majority of dogs. In a few animals, intermittent perfusion was used to restore the blood loss.

*The studies on shock verified by Blalock, Allen, Adams, Lillehei and others, have been used as the basis for this investigation. The word "depressed" is used in caution, considering the nature of our experiments, but we also use the word "shock" in our clinical cases.

In a group of 25 dogs treatment was administered exclusively by perfusion, the blood being totally replaced by this method. With this group the technique was changed. The perfusion was accomplished by means of a plastic tube with multiple small perforations in the portion which enters the abdominal region.

II. *Intravenous and Intra-arterial Transfusion Under Pressure.*—Two hundred and fifty animals were treated by these methods. The blood used was oxygenated and heparinized. A polyethylene tube, corresponding in size to a No. 18 needle, was introduced into a femoral vein or femoral artery for a length of 6 cm.

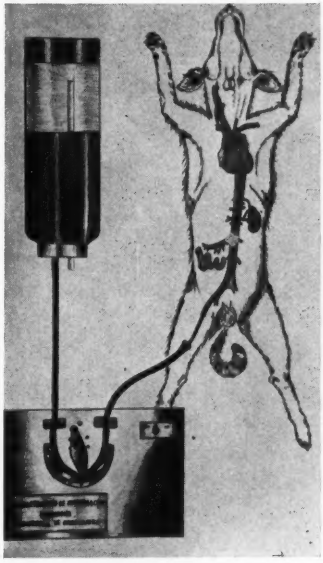

Fig. 1.

RESULTS

A comparison of survival and mortality results obtained to date in different groups and observations verified in experimentation follow.

Control Group.—

a. Treatment: Intravenous transfusion under pressure immediately after blood drainage; 132 animals were subjected to this procedure. Four animals, or 3.03 per cent, survived; 128 animals, or 96.07 per cent, died.

b. Treatment: Intra-arterial transfusion, immediately after blood drainage; 118 animals were subjected to this procedure. Six animals, or 5.08 per cent, survived; 112 animals, or 94.02 per cent, died.

Coronary Perfusion Group.—

a. Therapeutic application immediately after blood drainage; 200 animals were subjected to this procedure. One hundred and eighty animals, or 90 per cent, survived; 20 animals, or 10 per cent, died.

b. Therapeutic application between 1 and 2 minutes after blood drainage; 15 animals were subjected to this procedure. Eleven animals, or 79 per cent, survived; 4 animals, or 21 per cent, died.

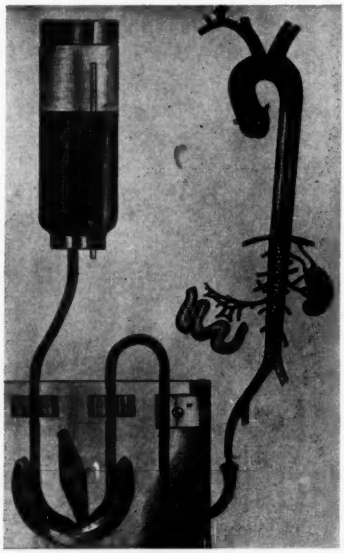

Fig. 2.

c. Therapeutic application between 2 and 4 minutes after blood drainage; 20 animals were subjected to this procedure. Six animals, or 30 per cent, survived; 14 animals, or 70 per cent, died.

d. Therapeutic application between 4 and 6 minutes after blood drainage; 15 animals were subjected to this procedure. Two animals, or 10.3 per cent, survived; 13 animals, or 89.07 per cent, died.

It is interesting to note that none of these dogs, subjected to massive blood loss, presented ventricular fibrillation.

Exclusive Perfusion With Abdominal Multiperforated Tube (Fig. 2).—

We consider our observations of this group incomplete. Taken into consideration was the problem of immediate abdominal irrigation achieved with the perfusion, so that the blood could pass to the intra-abdominal, coronary, and encephalic circulation, simultaneously.

The number of animals in this group is small in comparison with the other experiments, but to date there have been no deaths in the 25 dogs studied. Experiences relating to the measurement of coronary, encephalic, and intra-abdominal fluids are not reported, having been initiated recently and, are therefore incomplete.

Manometric Studies Relating to Blood Volume Loss Under I^{131} and Iodized Albumin Control.—

Volumetric losses of from 90 to 95 per cent were obtained in between 8 to 12 minutes. Arterial pressure dropped to 30 mm. Hg, although we consider the onset of depression to be when the volume of blood loss reaches 40 or 50 per cent. A pressure of zero was generally obtained when the animal had lost from 60 to 65 per cent of its blood volume. Some dogs presented heart arrest with very slow respiration when the loss of volume rose to 95 per cent. Several recovered spontaneously from the arrest when perfusion was applied.

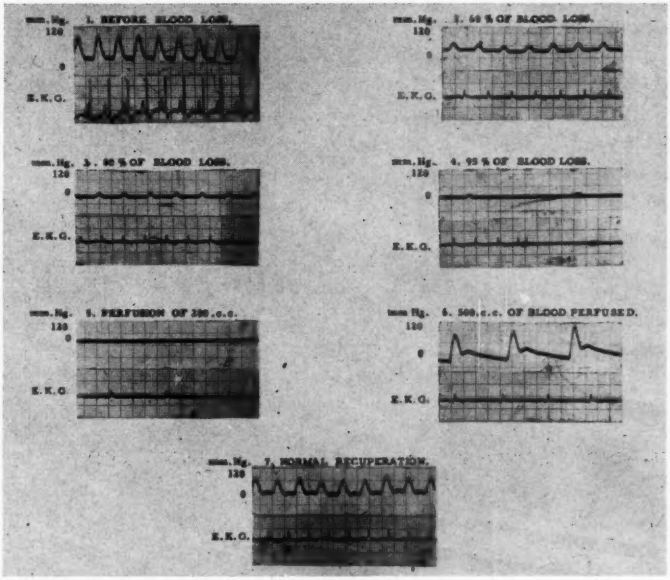

Fig. 3.

Electrocardiographic Studies (Fig. 3).—

The electrocardiogram generally demonstrates the abatement of the complexes when the volume of blood loss reaches 60 per cent. Inversions of T waves were observed when the hypotension was prolonged. The electrocardiogram tends to return to normal in relation to the increase of blood volume administered to the animal. The improvement observed with perfusion is remarkable, principally in the elevation of the complexes and stabilization of the T wave. We believe we have evidence that the electrocardiographic improvement is more conspicuous and rapid during perfusion than later after the blood has been totally restored.

Electroencephalographic Studies.—

The graphic decrease of the complexes during blood drainage, as relative horizontal is reached with a blood loss of 95 per cent, was clearly demonstrated.

As recuperation is initiated by perfusion, the electroencephalic curve also recovers with the rise in blood pressure.

Desoxycorticosterone Studies.—

When the systolic pressure of the animal reaches 30 mm. Hg, the desoxycorticosterone shows considerable elevation. Later, as the arterial pressure continues to drop, the desoxycorticosterone descends almost to zero. It rises again almost immediately when normal arterial pressure is re-established by the administration of blood. We have observed that, once the experiment is terminated and the arterial pressure totally restored by the replacement of blood, the desoxycorticosterone figure was always less than normal.

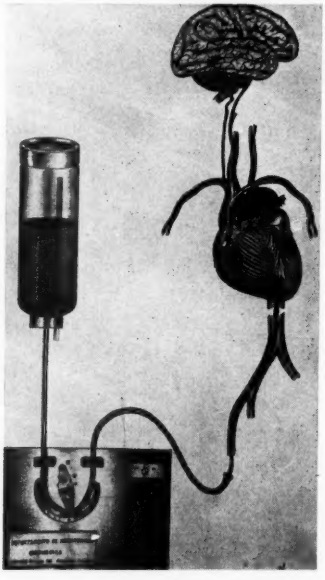

Fig. 4.

CLINICAL EXPERIENCE

To date, 50 patients have been treated in our surgical services. Perfusion was administered by means of a polyethylene or polyvinyl tube which was introduced into the first portion of the descending thoracic aorta through a transverse incision of one of the femoral arteries. In 2 cases, a transverse incision of the brachial artery was employed. All patients, even if hemorrhagic, were previously prepared by an intravenous injection of heparin, 2 mg. for each kilogram of weight. In some cases the blood was pumped with the Kay-Anderson pump, and in others our own pump was used. In 4 cases, because of special circumstances of an emergency character, we were obliged to use a 100 c.c. syringe to introduce the blood under pressure (Fig. 4).

In some cases ordinary citrated venous blood was administered and in others oxygenated and heparinized blood was used. Although to date it has

not been possible to discover clinically any marked difference in the employment of these two methods, we have the impression from results obtained in animals that, in cases of grave depression, there may be some advantage in the use of oxygenated, heparinized blood.

The amount of blood used varied from 60 c.c. to 1,000 c.c. a minute, depending upon the case. The total quantity of blood used in a perfusion varied from 300 to 1,500 c.c. In all patients, intravenous transfusion of blood was continued after the arterial pressure rose to between 80 and 100 mm. Hg.

Patients treated in this manner have been divided into two groups.

Group I.—Acute: 28 patients in shock received treatment as follows: (a) traumatic emergency—5 cases, no deaths; (b) transoperative application—4 cases, no deaths; (c) postoperative application—14 cases, 1 death; and (d) post-partum application—5 cases, 1 death.

Perfusion was resorted to after venous transfusion, and, in 2 cases after arterial transfusion failed to obtain results. In 2 cases, one a post-partum hemorrhage and the other an injury of the subclavian artery, we were obliged to open the thorax and apply cardiac massage because of cardiac arrest. We believe the important factor in the recovery of both of these patients was that the massage, as well as perfusion, was applied in the course of the first few minutes after the onset of the arrest.

Of the 28 patients in group I, 2 died; one after a radical pelvic operation and one of a massive post-partum hemorrhage. In both instances shock had probably been present for some time. The post-partum patient was brought to the city 3 days after the mishap with symptoms of shock for the previous 6 hours.

After termination of the surgical procedure all patients of group I were treated with protamine, 2 mg. for each kilogram of weight.

Group II.—Preventive Application (Table I): We have used this method only during the past year. The procedure is applied to patients subjected to major surgical intervention in which the recognized risk of probable shock during operation exists, difficult to control by any means known at present. This situation is frequently complicated further by the precarious general condition of the patient which is due to a lifetime of nutritional deficiency. Surgical intervention was indicated for various pathologic processes: cancerous invasions; pleuropneumonectomy for destructive, toxic tuberculosis; massive intestinal resection for chronic conditions, such as extensive colectomies for ulcerative lesions with persistent hemorrhage, unresponsive to medical treatment, or extensive polyposis of the large intestine for which ample resection was indicated. The general condition of many of these patients was deplorable; presurgical preparation, although prolonged and including repeated blood transfusion, had proved unsatisfactory. This group was carefully selected, taking the shock control factor as the criterion. We have systematically refused preventive application of this method to patients who, although presenting a risk of shock during operation, have not been considered problems for control by the usual methods of blood transfusion.

TABLE I. PREVENTIVE APPLICATION

SURGICAL PROCEDURES	NO. OF CASES	DEATHS
Esophagectomies	3	0
Transthoracic gastrectomies	1	0
Pneumonectomies	3	0
Pleuropneumonectomies	2	0
Gastrectomies	4	0
Hysterectomies	4	0
Colectomies	3	0
Splenectomies	2	0
Totals	22	0

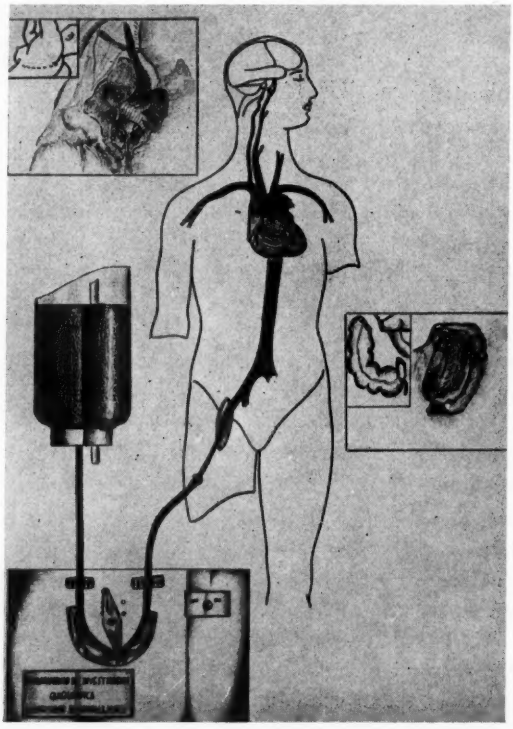

Fig. 5.

In no patient accepted was the systolic pressure higher than 90 mm. Hg after preoperative preparation. The ages varied from 23 to 60 years. The procedure used in these cases follows (Fig 5).

Before surgery, the patient received a dose of heparin 2 mg. for each kilogram of weight. This was followed immediately by a transverse incision in the femoral artery in the upper third of the thigh through which the plastic tube was introduced and passed to the descending thoracic aorta. This tube is connected to the pump tube, full of oxygenated, heparinized blood, 18 mg. of

heparin for each 500 c.c. In some special cases citrated venous blood was transfused by means of a syringe. The surgical procedure was initiated. When arterial pressure dropped considerably we perfused from 80 to 150 c.c. of blood. Almost immediately in most cases, although in some there may be a delay of 2 or 3 minutes, the pressure rose until the preoperative figure was regained, or rose, in some cases, 10 to 20 mm. Hg higher. After return to normal pressure the application of venous blood was the usual procedure. The perfusion may be re-instituted as frequently as necessary when, and if, arterial pressure drops.

In the 22 patients studied with this technique, there has been no interruption of the surgical procedure, although in each of them perfusion has been applied at least four times. Three of these patients presented during surgery a systolic pressure reading below 50 mm. Hg eight different times during the operation. Perfusion was applied each time, using from 80 to 200 c.c. of blood.

Only in 2 cases did the quantity of blood applied both by perfusion and by vein reach 2,000 c.c.—1,000 c.c. by perfusion and 1,000 c.c. intravenously. In the remainder, the quantity of blood employed was between 1,000 and 1,500 c.c., the ratio remaining the same—half by perfusion and half by vein.

In 2 cases the blood was applied solely by perfusion. One of these was after a pneumonectomy in a 23-year-old married woman, mother of five, whose left lung was destroyed by tuberculosis with mediastinal deviation. After 5 months of preparation, based on specific medication and reconstructive therapy to improve her general condition, this patient was brought to surgery weighing thirty-eight kilograms, with an arterial pressure of 80 systolic and 60 diastolic. Massive introduction of blood was not feasible, yet the prevention of shock was imperative. Pneumonectomy was performed, only 800 c.c. of blood by perfusion being used during the procedure. After surgery, with a pressure of 100 systolic and 70 diastolic, the patient was given another half liter of blood; during the night another half liter was administered. Two months after surgery this patient is progressing satisfactorily.

The other patient had had a gastrectomy for ulcer and had received only 800 c.c. of oxygenated blood by perfusion during the surgical procedure.

All patients were treated with protamine sulfate, 2 mg. for each kilogram of weight, immediately after surgery. No bleeding complications occurred during or after the operations. There were no deaths in this group.

COMMENT

Studies carried out in our laboratories and clinical services during the past 5 years lead us to believe in the possibility of a new application of perfusions made available by extracorporeal circulation.

We believe that for years all of us have realized the advantages of a more effective use of blood transfusions for patients during surgical procedures or in shock. It is indisputable that the intravenous transfusion is a procedure to which humanity and the surgeon owes much; but we are also aware that intravenous

transfusion frequently does not fulfill our requirements, and may even complicate certain situations—at times because of an excess of liquid, and again from the failure of direct action upon the cardiac muscle and encephalic centers. For an intravenous transfusion to reach these centers it is necessary for the blood to make a circuit throughout the body from the inlet, first passing through the cardiac cavities and the lungs, the myocardium and encephalon receiving no blood until after it leaves the left ventricle.

It may happen, especially in shock, that, because of the depressive condition itself, the right ventricle cannot eject or pump all the blood received by transfusion; the lungs cannot discharge the contained liquid and the left ventricle is also unable to pump properly. It is our belief that this condition is reflected in a decrease of the coronary and encephalic fluid, as has been demonstrated in many laboratories including ours. We have the firm belief that the tonicity and hemodynamic capacity of the ventricles should logically be elevated before these cavities receive a quantity of blood to be pumped immediately.

The first procedure which solved, in part, the problem of the blood reaching these centers in the form indicated was the intra-arterial transfusion. However, our experience, herein reported with the intra-arterial transfusion under pressure and transfusion by perfusion supports the premise that by the intra-arterial transfusion procedure a sufficient amount of blood does not reach the myocardium and encephalon. The idea of placing the plastic tube in the superior third of the descending thoracic aorta for the transfusion pumped has as its objective a major utilization of the fluid by these two centers. We believe that a short sound may be used, as in extracorporeal circulation, but in experiments we have made in animals, not herein reported, a much larger quantity of blood is required.

It is not our desire to circumscribe the therapeutics in these depressed states. We continue to believe that peripheral collapse is an important factor, which is the reason we also utilize venous introduction of blood or the abdominal multiperforated plastic tube in perfusion.

As we emphasized, from the experimental as well as from the clinical aspect the animals treated to date have been selected to emphasize the following: the animals were subjected to massive blood loss, subsequently treated by the introduction of blood, in part by ordinary methods, such as intravenous and intra-arterial transfusions, in part by coronary-myocardiac and encephalic perfusion. We believe more satisfactory results were obtained by the latter method. Clinically we observed two acute groups; one in which the usual methods employed would not have solved our problem, the other a preventive application group which contained patients who formerly would have been considered great operative risks or even inoperable.

It is our intention that this report be considered a review of our experimental investigations, interesting only in that it may be an indication for new techniques in the problem of utilization of blood in depressed states.

We extend our deep gratitude to Mrs. Lorraine Small de Chavez for her splendid cooperation.

Heparin (Liquemine) and protamine sulfate were kindly supplied by Hoffman-La Roche, Inc., Basilea, Switzerland.

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TERATOID TUMORS OF THE MEDIASTINUM FOUND DESPITE PREVIOUS NORMAL CHEST RADIOGRAPHY

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We present 2 patients with large teratoid tumors of the mediastinum, which were successfully removed 2 and 4 years after chest radiographs, taken for routine purposes, had shown no abnormality.

CASE REPORTS

CASE 1.—J. A. was admitted to Victoria Hospital, Blackpool, on July 16, 1954, when she was 21 years of age. She gave a history of left chest pain, fever, and effort dyspnea for 1 month before admission; toward the end of this time a small cystic swelling appeared at the sternal notch (Fig. 1) which, on aspiration, was found to contain opaque fluid containing large numbers of cholesterol crystals, but no pus cells or organisms, and was sterile on culture. There was no significant previous medical history. A chest radiograph, taken as a condition of her employment 2 years previously, had been normal (Fig. 2).

On admission to hospital, chest radiography revealed a large mass projecting from the anterior mediastinum into the left hemithorax (Fig. 3). The heart was greatly enlarged, and, on screening, pulsation was diminished, suggesting a pericardial effusion. At left thoracotomy (July 28, 1954; J. S. G.), a large mass with a smooth surface was seen to be confluent with the pericardium and the mediastinum. The pericardium was distended and 100 c.c. of hemorrhagic fluid were removed by aspiration. The main mass was punctured and some yellowish granular material with thin, apparently purulent, fluid escaped. The mass was firmly adherent to the mediastinum, and was dissected with difficulty. The patient's postoperative recovery was uneventful, and subsequent chest radiographs have been normal.

Macroscopic examination showed a large cyst, measuring 12 by 11 cm., with flakes of bright yellow material adherent to the inner lining. The wall was thickened and fibrosed; the cavity was unilocular showing two or three large pockets containing bright yellow material. There were two prominent masses of tissue covered with normal skin and hair projecting from the inner lining, probably mammillae. A section of one of these showed a central core of fat covered with skin; a second mass at the base also contained skin. A section of the wall, which was 1 cm. thick, showed marked fibrosis with bright yellow foci.

Microscopic examination of a section of the wall showed skin, sebaceous gland, and hair follicles. In the deeper part of the wall there were areas of adipose tissue, lymphoid tissue, plain muscle fibers, cartilage, mucus and mixed glands, and one large space was lined with respiratory pseudostratified ciliated epithelium (Fig. 4, *A* and *B*). There was no evidence of malignancy or of inflammatory change.

Diagnosis.—Benign cystic teratoma of the mediastinum.

From High Carley Hospital, Ulverston, and Victoria Hospital, Blackpool, England.
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Fig. 1.—Case 1. The swelling in the suprasternal notch is shown.

Fig. 2.—Case 1. Miniature chest radiograph of July, 1952, was considered normal.

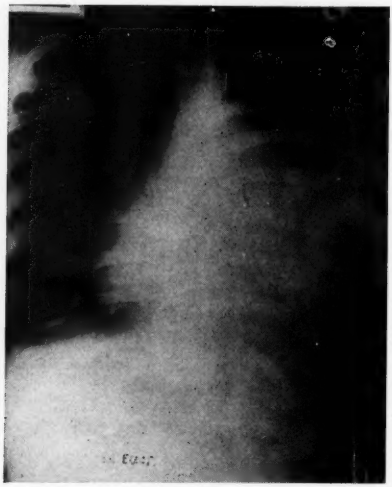
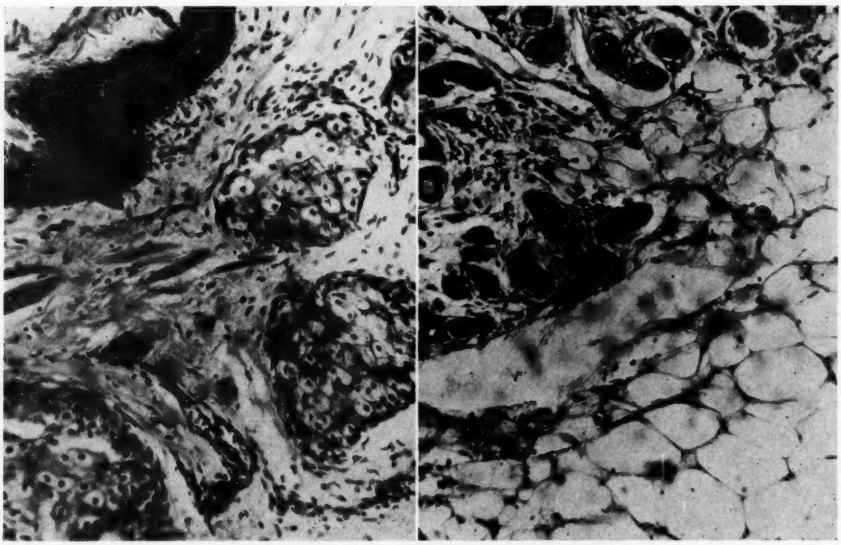


Fig. 3.—Case 1. Posteroanterior chest radiograph made in July, 1954.

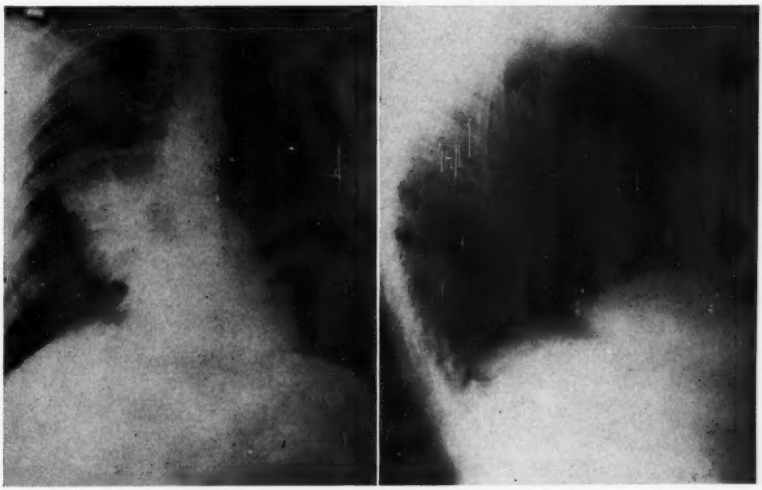


A. *B.*

Fig. 4.—Case 1. *A* and *B*, Photomicrographs (high power and hematoxylin and eosin stain) which show sebaceous glands, respiratory pseudostratified epithelium, adipose tissue, and mucus and mixed glands.

CASE 2.—J. P., a 37-year-old foreman shipwright, was admitted to High Carley Hospital on June 16, 1958, with a history for the previous 6 months of intermittent substernal pain, sometimes referred to the right side of the neck and brought on by bending or twisting. He was otherwise free of symptoms. There was no relevant previous medical history; a miniature radiograph taken in November, 1954, was normal. On admission to hospital, a chest radiograph showed a dense lobulated well-defined shadow in the right mid and lower zones (Fig. 5, *A*), and seen on the lateral view to lie anteriorly (Fig. 5, *B*) and continuous with the mediastinum.

At right thoracotomy (July 16, 1958; J. S. G.), a large anterior mediastinal tumor was found, which did not involve the lung. This was shelled out without difficulty, and the patient's postoperative course was uneventful. He has since remained free of symptoms and his chest radiograph is normal.



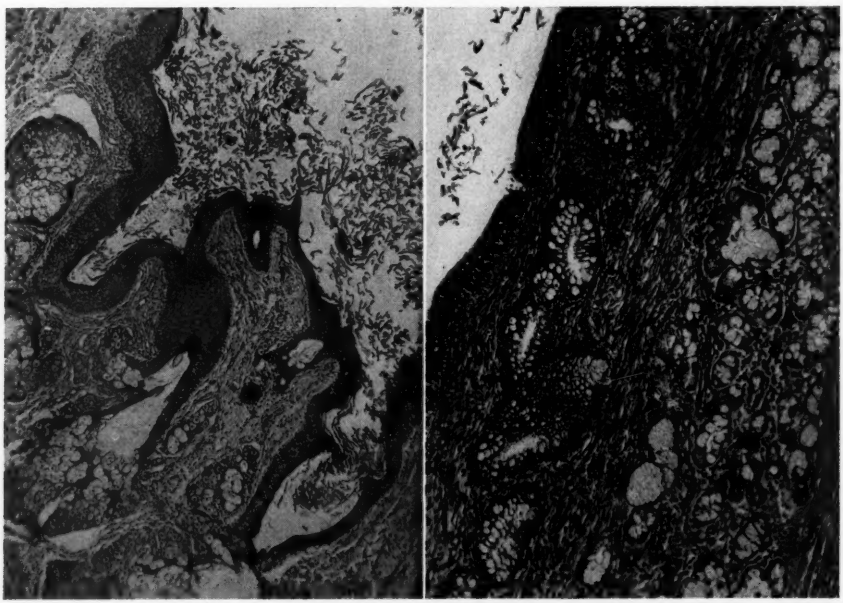
A. *B.*

Fig. 5.—Case 2. Lateral chest radiograph *(A)* and posteroanterior chest radiograph *(B)* made on June 13, 1958.

Macroscopic examination showed an encapsulated tumor of ovoid shape, weighing 290 grams (Fig. 6). It was smoothly encapsulated, but the capsule was roughened by adherent pieces of pleural membrane. It measured 10 by 7 by 8 cm. The cut surface showed a variegated multicystic pattern; the cysts were small, the maximum measuring 1.5 cm. in diameter. Many of the cysts were filled with coagulated mucus and others contained watery fluid. The firm tissue varied markedly in consistency and color. In some areas there was a marked lipoid element; other parts were composed of very white soft tissue suggestive of cerebrum, but others were of much firmer nondescript material. The appearance was typical of dermoid tumor.

Microscopic examination (Fig. 7, *A* and *B*) of the tumor showed a capsule of thick fibrous tissue, rich in blood vessels. The tumor itself was composed of a multiplicity of tissues which had reached an adult form of development, apart from occasional areas showing less well-differentiated tissue; for example there was one piece looking very like embryonic lung epithelium. The following structures could be identified; skin; sebaceous glands and hair follicles; respiratory epithelium; embryonic lung tissue and cartilage; nerve, brain, and choroid; smooth and striped muscle, fat, vascular channels, and lymphoid follicles. The tumor was histologically benign.

Fig. 6.—Case 2. Macroscopic picture of specimen which shows multiple small cysts.



A. *B.*

Fig. 7.—Case 2. *A* and *B*, Photomicrographs which show multiplicity of tissues which compose the tumor.

DISCUSSION

Rusby[3] reviewed 245 cases of teratoid tumor from the world literature and added 7 of his own. He referred to the importance of an increase in size of a teratoid tumor as an urgent indication for surgical resection, in view of the possible development of malignancy. Eleven and nine-tenths per cent of the 252 cases proved to be malignant, although this change was not necessarily associated with a recognized increase in size.

More recently, Morrison[2] found 36 teratoid tumors in a series of 332 cases of tumors and cysts of the mediastinum; 3 of 36 were malignant.

We have been unable to find any reference in the literature to the development of evidence of a teratoid tumor after previous chest x-ray studies had been normal; our 2 cases demonstrate that this diagnosis is not in fact excluded by a previous normal radiograph.

The cause of the quite rapid enlargement of the tumors remains a matter for speculation. It must be assumed that an embryological rest was present at the time of the normal radiograph; yet after an interval of only 2 years, the first patient showed evidence of a cystic tumor measuring 12 by 11 cm., while in a second patient, a tumor, measuring 10 by 8 by 7 cm., had developed after a 4-year interval. The first tumor contained one large cystic space, while the second contained numerous small cysts and much solid tissue.

In neither tumor was there any evidence of malignancy or of acute infection, and it seems that the accumulation of fluid in the cystic spaces accounted for only a proportion of the enlargement noted.

Willis[4] points out that in a small proportion of mediastinal teratomas, the pericardium is involved, as in our Case 1, and adds that the majority of these patients present symptoms in infancy or childhood. Discussing the maturation of tissues in teratomas, he says, "Malignant teratomas contain embryonic tissues of varying degrees of immaturity, often along with maturing and well-differentiated ones. The mixture of differentiating tissues of all ages is one of the most striking features of actively growing teratomas. Now, while the presence of immature tissues in a teratoma in an adult is clear evidence of its continued proliferation and probable malignancy, this does not necessarily apply to a similar growth in a foetus or young infant, whose own normal tissues are themselves still immature." The lack of evidence of malignancy in our cases is notable, although some immature tissue was found in the specimen of Case 2.

The appearance of a cystic swelling in the suprasternal notch in Case 1 appears to be somewhat unusual, although Hedblom[1] refers to 19 similar instances collected from the literature.

SUMMARY

Two patients are described from whom large teratoid tumors were removed 2 years and 4 years after a routine chest radiograph had proved to be normal. There was no evidence of malignancy or of acute inflammation in either tumor, and the cause of the rapid increase in size remains a matter for speculation.

Our thanks are due to Dr. A. A. Miller for the report on the specimen on Case 1, and to Dr. A. Rickards for the report on the specimen on Case 2.

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ESOPHAGOPLEURAL FISTULA AS A COMPLICATION OF THORACIC SURGERY

A Collective Review

Timothy Takaro, M.D., Harry E. Walkup, M.D., and Takeshi Okano, M.D., Oteen, N. C.

THE appearance of an esophagopleural fistula following thoracic surgery for nonmalignant disease has been rarely reported in this country; only four instances have been recorded to our knowledge.[1-3] When 2 patients with esophagopleural fistulas were treated simultaneously in our hospital recently, it occurred to us that perhaps this complication was not, in fact, as rare as the paucity of reports seemed to indicate. The purpose of this review is to show that this complication has followed thoracic surgical procedures in a good many centers in this country. It is hoped that analysis of all available cases may throw some light upon the pathogenesis of this distressing condition and may serve as a guide for treatment and, if possible, for prevention.

A questionnaire was prepared and mailed to 122 thoracic surgeons in the United States and to 1 in India, regarding the development of esophagopleural fistulas in association with thoracic surgery. Replies were received from 69 surgeons, 28 of whom answered affirmatively and contributed clinical material for this study.

Data on 33 cases of esophagopleural fistula following intrapleural* surgical procedures thus became available for review. Twenty-four of these followed a pneumonectomy, all but three occurring on the right side. Five followed lobectomies of various kinds. Single instances of fistulas occurred following hiatus hernia repair, thoracic aneurysm resection, removal of bronchogenic cyst, and lysis of adhesions during intrapleural artificial pneumothorax were also reported.

PATHOGENESIS

The primary disease was pulmonary tuberculosis in 22 of these patients and suppurative disease in 6. A bronchial adenoma accounted for a single case, and the hernia, the aneurysm, and the bronchogenic cyst accounted for 3 others. In one instance, the etiology of the primary disorder was unknown to us.

From the Veterans Administration Hospital, Oteen, N. C.
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*The word "intrapleural" is used for the sake of simplicity, to distinguish these operations from those purely chest wall extrapleural procedures, such as thoracoplasty or extrapleural pneumonolysis. A small number of extrapleural pneumonectomies or pleuropneumonectomies are included in this "intrapleural" group.

In 16 cases, the fistula was diagnosed within 3 months of surgery (within 1 month in 10 cases). Operative injury to the esophagus was recognized at surgery or autopsy in 5 of these patients. In 3 others it was noted that the esophagus was intimately related to the lesion being resected, but no injury was recognized. The surgical procedure was difficult in at least 5 other cases, a pleuropneumonectomy or a completion pneumonectomy (following a previous lesser resection) being the operation performed. One can assume with some assurance that surgical trauma contributed directly to the development of esophagopleural fistula in most of these 16 cases. The primary disease was tuberculosis in only half of them (50 per cent).

In the remaining 17 cases, the fistula was diagnosed from 3 months to 6 years following the major thoracic operation, save for 1 case in which there was incomplete data on this point. In these 17 patients, the primary disease was pulmonary tuberculosis in 14 (82 per cent). At least 11 were known to have developed a bronchopleural fistula and/or empyema postoperatively. Thus, chronic infection almost certainly played a major role in most instances in this group.

INCIDENCE

One suspects that this complication occurs mueh more commonly than the scanty reports in the literature would indicate. Nearly half of the 69 surgeons who sent replies to our questionnaire were able to report cases of this complication—in some instances, several cases. At the Veterans Administration Hospital in Oteen, North Carolina, during the past 12 years, 4 cases were seen in a group of 934 resections for pulmonary tuberculosis. Most of the total of 33 cases collected occurred in the past 5 years.

CINICAL PICTURE AND DIAGNOSIS

There appears to be no typical clinical picture of the development of this complication. The onset was commonly more abrupt in instances in which the fistula occurred soon after surgery, and more insidious in later-appearing fistulas. Symptoms developing soon after surgery often suggested the clinical picture of a bronchopleural fistula or empyema. Fever and chest pain usually occurred at the onset–subcutaneous emphysema, occasionally. The finding of food particles or previously ingested fluid in pleural drainage was commonly the first sign of the presence of a fistula, and is pathognomonic. It was usually readily verified by the observation in pleural drainage of previously ingested methylene blue, or by the ingestion of barium cr Lipiodol, and radiography. Severe weight loss and even emaciation were features in some of the chronic cases, but these were not constant.

The level of the fistula, as identified roentgenographically or at autopsy, was in the mid-esophageal area at or near the tracheal bifurcation in 15 patients who underwent resection for tuberculosis, and in 4 others who had nontuberculous conditions (Fig. 1). There were four fistulas in the lower third of the esophagus in tuberculous patients, and four in nontuberculous cases. In the remainder, the level of the fistula was not identified.

TREATMENT AND RESULTS

Treatment was varied, and complicated, with multiple procedures in many patients. This makes analysis somewhat difficult. In general, however, direct attacks on the fistula, by suture or by muscle-implants in 8 patients led to partial or complete success in 7, with one death. Four attempts to reconstruct an esophagus from segments of colon, jejunum, or stomach resulted in fatalities. In 10 patients, only chest wall surgery, including drainage, Schede thoracoplasty, etc., were performed as definitive treatment, with two deaths. In 10 others, definitive surgical treatment (other than jejunostomy or gastrostomy in some) was not carried out. In this group there were nine deaths. The over-all mortality rate was 49 per cent.

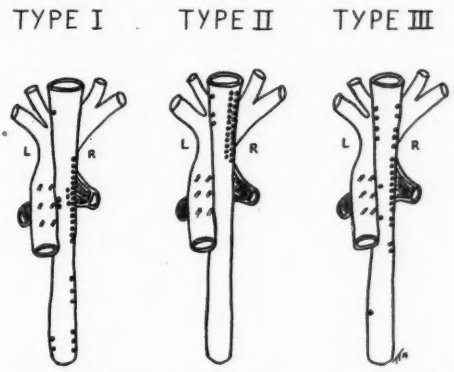

Fig. 1.—Diagram indicating approximate level and side on which 81 esophagopleural or extrapleural-esophageal fistulas occurred. *Type I:* Fistulas following intrapleural operations, but including also extrapleural pulmonary resections. *Type II:* Fistulas following extrapleural operations such as thoracoplasty and extra pleural pneumonolysis, but not including extrapleural pulmonary resections. *Type III:* Fistulas following chronic empyema not associated with major thoracic surgery.

Complete cure, with no residual sinus, empyema space, or fistula, was achieved in only 5 tuberculous patients. Chest wall surgery of the Schede thoracoplasty or sinus excision type was performed in 2 cases, and in combination with these procedures, a muscle flap operation, direct closure of the fistula and excision and re-anastomosis of the esophagus, were successful in the other 3. One nontuberculous patient was successfully treated with closed suction drainage and another by thoracoplasty. The primary disease in the latter was not known to us. The over-all cure rate was 21 per cent. The remaining survivors retained a draining sinus, fistula, or empyema space. These data are summarized in Tables I, II, and III.

CASE REPORTS

CASE 1.—C. M., a 37-year-old white man, was admitted to the VA Hospital at Oteen, North Carolina, in 1949 for closure of a Monaldi cavernostomy.

In 1944, the patient had had resection of a mediastinal neurofibroma from the right paravertebral gutter at the fourth thoracic vertebral level, which was "pressing on the esophagus." Recovery was apparently uneventful. The onset of pulmonary tuberculosis

TABLE I

CASE NO.	MAJOR OPERATION PRECEDING FISTULA	OPERATIVE AND POSTOPERATIVE COURSE	INTERVAL BETWEEN OPERATION AND DIAGNOSIS OF FISTULA	TREATMENT	RESULTS
	A. Esophagopleural Fistulas Following Resections for Pulmonary Tuberculosis				
1	Right pleuropneumonectomy	BPF; thoracoplasty	17 months	Jejunostomy; Schede thoracoplasty	Cured
2	Right pleuropneumonectomy	BPF; empyema; rib resection	7 weeks	Gastrostomy; direct closure (failed), resection and end-to-end anastomosis	Cured
3	One prior resection; completion right pneumonectomy	Difficult operation; empyema; open drainage	3 weeks	Gastrostomy; cautery	Fistula persists
4	Prior resection and thoracoplasty; completion left pneumonectomy	BPF; Schede thoracoplasty; spread	8 months	Jejunostomy	Died; extensive tuberculosis remaining lung
5	RUL; superior segment, RLL; Wedge, RML	Empyema; thoracoplasty; open drainage; Schede	3 years	Gastrostomy twice; laparotomy (intussusception)	Died; gastrojejunal fistula
6	Prior resection and empyema; completion right pneumonectomy	Difficult operation; intrapericardial ligation of torn pulmonary artery	Less than 2 months	Gastrostomy thoracoplasty; secondary bronchial closure; jejunal bypass operation	Died
7	Prior resection and BPF; completion left pneumonectomy	BPF; empyema	17 months	Gastrostomy	Died soon after gastrostomy
8	Right pleuropneumonectomy	Empyema; rib resection	6 years	Gastrostomy; 2-stage thoracoplasty	Alive with gastrostomy
9	Right pneumonectomy	Oleothorax established postop.	2½ years	Gastrostomy; open drainage	Died 3 months after diagnosis
10	Right pleuropneumonectomy	Extensive dissection	8 months	Gastrostomy; Schede thoracoplasty, skin graft	Alive and working; fistula persists 6 years
11	Right pleuropneumonectomy	BPF; Schede thoracoplasty; muscle flap	2½ weeks	--	Died 5 days after fistula diagnosed
12	RU lobectomy and RM lobectomy	Empyema; open drainage; thoracoplasty	Approximately 1 year	--	Died; condition too poor for surgery
13	Pneumonectomy	Empyema	Few days	--	Died; autopsy: esophageal injury unrecognized at surgery
14	Right pleuropneumonectomy	Empyema—drained	7 days	Gastrostomy; jejunostomy; thoracoplasty; Schede thoracoplasty; several attempts at direct repair; colon bypass	Died—complete separation of both anastomoses

15	Right pneumonectomy	3-stage thoracoplasty	18 months	Fistula excised; wall of esophagus closed	Alive; fistula reopened, closed
16	Two prior resections; completion, right pneumonectomy plus pleurectomy	Localized empyema found at operation; esophagus carefully identified	4 days	Closed, then open drainage	Alive; drainage continuing 1 mo. postop.
17	Right pneumonectomy	BPF; empyema	11 months	--	Died 2 mo. after diagnosis
18	Prior resection, mediastinal tumor; prior 3-stage thoracoplasty plus Monaldi; right pneumonectomy	Difficult operation, BPF; empyema; rib resection	22 weeks	Jejunostomy; Schede thoracoplasty	Alive; fistula closed; 6 year follow-up
19	Left pneumonectomy	Difficult operation; BPF; empyema, open drainage	16½ months	Tube feedings only	Died, cavitary disease, opposite lung
20	Prior resection and thoracoplasty; completion right pneumonectomy	Esophagus mobilized inadvertently; empyema; open drainage	20 weeks	Schede thoracoplasty and revisions	Died 2½ years later
21	Prior resection; 3-stages of thoracoplasty; completion, right pneumonectomy	Lung densely adherent; febrile postop. course	12 weeks	Open drainage; Schede thoracoplasty and revisions	Alive; fistula persists 2½ years
22	Intrapleural lysis of adhesions, left	--	--	Gastrostomy; thoracoplasty; muscle flap	Recovered
	B. Esophagopleural Fistulas Following Operations for Nontuberculous Disease				
23	Removal of bronchogenic cyst	Esophagus stretched over cyst	5 weeks	Gastrostomy; rib resection; decortication plus pleural flap	Alive; residual sinus
24	Suppurative disease; right pneumonectomy	BPF	3 weeks	Pleural flaps (failed); 2-stage thoracoplasty	Alive; residual empyema
25	RML and RLL for bronchiectasis	Difficult operation	11 days	Tube feedings; closed drainage	Recovered
26	Repair of hiatus hernia	--	6 days	Primary repair failed Esophagogastrostomy failed	Died
27	RML and RLL for bronchiectasis + cysts	Esophagus injured	5 days	Tube feedings	Alive; residual empyema, 7 years
28	RU lobectomy for lung abscess	Esophagus injured; empyema	10 weeks	Multiple Schede operations	Alive; residual space
29	Pneumonectomy	--	9 months	Thoracoplasty	Recovered
30	Resection, aortic aneurysm	Esophagus injured; repaired at initial operation	5 days	--	Died
31	Right pleuropneumonectomy for lung abscess	Abscess opened at operation	3 years	Gastrostomy; rib resection; cautery	Alive; fistula persisted
32	Right pneumonectomy for bronchial adenoma	BPF; bronchus resutured with wire	1 month	--	Died; wire suture eroded esophagus
33	Right pneumonectomy for lung abscess	Difficult operation	2 years	Gastrostomy; empyema drainage; 2 attempts to repair; colon bypass operation	Died; bypass operation unsuccessful

Notes: Case 1—Ref. 2; Case 2—Ref. 3; Cases 3-17—contributed (see acknowledgments); Cases 18-21—VA Hospital, Oteen, N. C.; Case 22—Ref. 63; Cases 23 and 24—Ref. 1; Cases 25-33—contributed (see acknowledgments).

Abbreviations: BPF—bronchopleural fistula. RUL—right upper lobectomy. RML—right middle lobectomy. RLL—right lower lobectomy.

TABLE II. ETIOLOGY AND DIAGNOSIS, NONMALIGNANT ESOPHAGOPLEURAL FISTULAS

TYPE OF FISTULA	ETIOLOGY OF PRIMARY DISEASE				INTERVAL BETWEEN SURGERY (OR EMPYEMA)* AND CLINICAL DIAGNOSIS OF FISTULA	
	PULMONARY TUBERCULOSIS	NONTUBERCULOUS DISEASE	UNKNOWN	TOTAL	LESS THAN THREE MONTHS	MORE THAN THREE MONTHS
I. Following intrapleural thoracic surgery	22	10	1	33	16	17
II. Following extrapleural thoracic surgery	33	0	0	33	4	29
III. Following empyema not associated with thoracic surgery†	10	20	5	35	14‡	15‡
Totals	65	30	6	101	34	61

*Applies only to Type III fistulas.
†Except drainage operations.
‡Data incomplete.

TABLE III. TREATMENT AND RESULTS, NONMALIGNANT ESOPHAGOPLEURAL FISTULAS

TYPE OF FISTULA	MANAGEMENT				OVER-ALL MORTALITY RATE	OVER-ALL CURE RATE‡
	PRIMARILY SURGICAL*		PRIMARILY MEDICAL†			
	NUMBER OF PATIENTS	DEATHS	NUMBER OF PATIENTS	DEATHS		
I.	22	6	10	9	49%	21%
II.	22	11	11	7	55%	19%
III.	12	4	24	14	51%	41%
Totals	56	21 (38%)	45	30 (67%)	51%	27%

*Thoracic surgery on chest wall or mediastinum, with and without gastrostomy or jejunostomy.
†With and without gastrostomy or jejunostomy.
‡Survivors with no residual fistula, sinus, or empyema space.

was in 1948, with bilateral disease, cavitary on the right. An anterior thoracoplasty and cavernostomy followed by two-stage posterolateral thoracoplasty were done at another hospital.

Soon after admission to Oteen, revision of the draining fistula in an attempt to close it was unsuccessful. Because of continuing positive sputum for acid-fast bacilli, the presence of a residual cavity under the thoracoplasty, and the draining cavernostomy, pneumonectomy was undertaken on Feb. 6, 1951. The operation was difficult. There was gross pleural contamination in cutting across the fistulous tract. The specimen contained caseocavernous lesions of tuberculosis. Approximately 2 weeks later, a bronchopleural fistula and tuberculous empyema were drained by a wide-open thoracotomy, resecting portions of five ribs. Five months later, food and fluid were noted to be draining from the thoracotomy wound. A pleuroesophageal fistula at the level of the sixth and seventh thoracic vertebrae was confirmed by barium swallow (Fig. 2). Since Levine tube feedings did not function well, a Witzel jejunostomy was done, and a modified Schede thoracoplasty to obliterate the space was carried out. Four months after discovery of the fistula, no more food or fluid was noted to be draining from the chest, and in another 2 months the pleural space had completely been obliterated. Nutrition had been fairly well maintained, the minimum weight (93 pounds) being about 30 pounds below the pre-pneumonectomy weight. At his discharge 10 months after the fistula appeared, his weight was 116 pounds.

He was seen again 6 years later, still thin, but fairly active. The right chest wounds had remained healed. Cold fluids produced a cold sensation over the thin skin covering the right mediastinum and chest wall. A barium swallow still showed marked diverticulum formation at the same level as noted 7 years earlier (Fig. 3).

CASE 2.—S. J. M., a 33-year-old white man, was admitted to the VA Hospital at Oteen, North Carolina, in June, 1953, for the treatment of pulmonary tuberculosis. The onset of his disease was in 1950 and was characterized by bilateral disease, with a 6 cm. cavity in the left upper and a 3.5 cm. cavity in the left lower lung fields. On Oct. 29, 1953, left pneumonectomy was carried out, in part by extrapleural dissection. The operation was difficult because of distortion due to marked mediastinal shift to the left, and dense adhesions. According to the surgeon's note, "Some difficulty was encountered in finding the inferior pulmonary vein until it was realized that the heart had shifted over and dissection was being carried out over the left auricle."

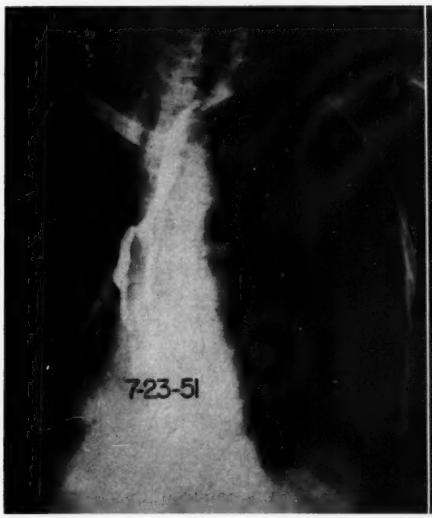

Fig. 2.

Fig. 3.

Fig 2.—Case 1. Mid-esophageal fistula opening into right pleural space diagnosed 22 weeks following right pneumonectomy which was complicated by the development of a bronchopleural fistula and tuberculous empyema. The fistula healed 4 months later, following modified Schede thoracoplasty.

Fig. 3.—Case 1. Esophageal deformity just proximal to the site of the fistula, 7 years later. Patient asymptomatic. Similar deformity was noted on this view 7 years earlier.

An empyema and bronchopleural fistula developed 3 weeks postoperatively which required first closed, then open, thoracotomy. In spite of drainage, the patient remained febrile and 8 weeks following the resection, unexplained spiking elevations of temperature were noted. Cultures from the empyema drainage were positive for acid-fast bacilli. There was no evidence of reactivation of disease in the opposite lung. Drainage and fever continued unabated for 6 months, and the patient's condition was deemed too poor for him to undergo thoracoplasty. Viomycin was added to his drug regime and he gradually improved, the empyema space diminishing in size. The bronchopleural-cutaneous fistula remained open. There was an episode of syncope in June, 1954. From July until December, 1954, the patient was afebrile. Thereafter elevation of temperature recurred again, ranging from 99° to 102° F. daily.

On March 9, 1955, 16 months following the resection, food and water were noted on his dressings for the first time. A barium swallow demonstrated the presence of an

esophagopleural-cutaneous fistula at the mid-esophageal level. In spite of tube feedings and parenteral fluid therapy, there were episodes of cyanosis due to regurgitation of secretions and fluids through the fistula into the remaining lung. The patient continued to lose ground and died 4 months after the fistula was discovered.

At autopsy, the patient weighed about 65 pounds. There was extensive caseocavitary tuberculosis in the remaining right lung with a large cavity communicating with the right pleural space. A 1 cm. defect in the esophagus a few centimeters below the main bronchus opened into the left pleural cavity. Microscopically, ulceration and granulation tissue formation were noted. An incidental finding of a liposarcoma of the right frontal lobe of the brain was noted.

CASE 3.—R. L., a 44-year-old white man, was admitted to the VA Hospital, Oteen, North Carolina, for the eighth time in 1956, for the treatment of pulmonary tuberculosis. The onset of his disease, in 1948, was characterized by bilateral disease with a large cavity in the right upper lobe, and tuberculous laryngitis. The patient was treated intermittently

Fig. 4.—Case 3. Autopsy specimen of mid-esophagus (opened) and tracheal bifurcation. A probe is visible in the wide esophageal end of the esophagopleural fistula several centimeters proximal to the level of the carina. This patient died 2½ years after diagnosis of the fistula.

with antimicrobial drugs (streptomycin, para-aminosalicylic acid, isoniazid) but treatment was repeatedly interrupted by irregular discharges. Finally in 1955, a right upper lobectomy and resection of the superior segment of the right lower lobe were done. This was followed 20 days later by a six-rib thoracoplasty for a residual apical space. The patient again left the hospital against advice, and was admitted a year later with a pulmonary hemorrhage. Bronchoscopy showed the presence of a bronchopleural fistula of the stump of the superior segment of the right lower lobe. Because of continuing streaking and atelectasis of the basal segments of the right lower lobe, the remainder of the right lung was resected on July 31, 1956. At this time sputum was negative for acid-fast bacilli.

During the course of the operation, which was difficult because of dense adhesions and the presence of a localized empyema in the superior part of the pleural cavity, according to the surgeon's note, ". . . the esophagus was inadvertently mobilized in its middle third, and the azygos vein was severed."

The postoperative course was febrile. On the eighth day after operation, as the sutures were removed, there was purulent drainage from the wound, and an empyema was drained the next day, at first by tube, then by open thoracotomy. Cultures of the empyema contents were negative for acid-fast bacilli, and there was never any clear-cut evidence of a bronchopleural fistula.

Drainage continued for some months. Exactly 5 months after the final resection, coffee which the patient had drunk was noted on the open thoracotomy drainage. The diagnosis of esophagopleuro-cutaneous fistula was made and confirmed by Lipiodol swallow. It was not identified, however, at esophagoscopy. A feeding tube was inserted into the stomach.

The fistula continued to drain small amounts of food and fluid for the next 2½ years, in spite of all attempts to obliterate the empyema space on the right side with Schede thoracoplasty and multiple revision operations. The patient was able to maintain his nutrition fairly well–eating normally without a feeding tube–the weight level being about 20 pounds below the pre-pneumonectomy level.

On Aug. 6, 1959, a final stage of modified Schede thoracoplasty was carried out to unroof completely the infected space. The postoperative course seemed uncomplicated except for moderate serosanguineous drainage from the wound. However, on the fifth postoperative day, 4 hours after a routine change of dressings, the patient was found dead in bed.

Autopsy did not reveal any adequate cause of death. There was a fistulous opening from the esophagus, approximately 3 cm above the level of the carina and about 1 cm. in diameter, into the empty right pleural space (Fig. 4). There was no evidence of bronchopleural fistula. Section through the fistula showed destruction of the esophageal wall with eversion of the mucosa toward the pleura. There was an esophageal gland near the area where the epithelium disappeared, joining inflamed pleura covered by a thick zone of mature granulation tissue.

CASE 4.—D. J. B., a 29-year-old Negro veteran, was admitted to the VA Hospital, Oteen, North Carolina, in 1954 for the treatment of pulmonary tuberculosis. The onset of his disease was in 1953, with cavitary disease of the right upper lung field. A 2-stage Lucite ball plombage thoracoplasty was carried out in November, 1954, with removal of the balls and 7 ribs on the right at the second stage. Because sputum remained positive for acid-fast bacilli and the cavity under the thoracoplasty persisted (shown by roentgenograms), resection of the right upper lobe and a portion of the superior segment of the right lower lobe was performed in April, 1955. A persistently infected subscapular space, with no evidence of bronchopleural fistula or empyema, was treated by a revision thoracoplasty in December of the same year. A suture granuloma of the right upper lobe stump was believed at first to be the source of the continuing positive sputum and hemoptysis. Following cauterization at bronchoscopy, the granuloma was observed to heal but sputum remained positive. Completion of the pneumonectomy was done on Feb. 5, 1957, and except for dense adhesions throughout the right pleural cavity, requiring sharp dissection, there were no unusual problems.

Following this operation, the patient ran a low-grade febrile course. Repeated attempts at pleural aspiration yielded no fluid. Three months later there was an episode of marked elevation of temperature and a roentgenogram showed an air-fluid level in the right pleural cavity. A closed thoracotomy with tube drainage yielded air and pus. The next day grape juice was noted in the drainage, and the diagnosis of esophagopleural fistula was made. It was verified by barium swallow and was noted to be at the level of the seventh to the eighth dorsal vertebrae. Tube feedings were begun and, 2 days after discovery of the fistula, an open thoracotomy was carried out. Nutrition was poorly maintained at first, with weight loss down to 80 pounds, and episodes of acute vascular collapse occurred which required parenteral cortisone therapy. Gradually the patient improved and over the next 2-year period the empyema space was obliterated by modified Schede procedures, exposing the fistulous opening with its firm, rounded edges (Fig. 5). In April, 1959, plastic closure of the esophageal fistulous opening which now

measured about 1 cm. in diameter was attempted but without success. A small esophagopleural fistula remains but the patient's nutrition has returned to much more nearly normal levels, his weight ranging up to 115 to 120 pounds.

DISCUSSION

There appears to be little doubt that in the 16 patients of the collected series, in whom the complication was recognized relatively promptly after operation, the esophagopleural fistulas were the result of surgical trauma, sometimes recognized, but usually not. It is a fact that in a difficult technical procedure, even when the possibility of esophageal injury is constantly borne in mind and the esophagus is carefully identified, injury and fistula formation may result.[4] The esophagus is often drawn to the side of maximal disease by contraction of fibrous adhesions or by lymphadenopathy. Occasionally this occurs

Fig. 5.—Case 4. Gross appearance of defect in esophageal wall communicating widely with small pleural pocket 6 months after diagnosis of esophagopleural fistula was made. The plastic feeding tube in esophagus is visible. This patient retains small fistula 2 years later.

in a sharply localized area. The degree and site of esophageal deviation can sometimes be identified with accuracy by a barium swallow prior to surgery (Fig. 6). The presence of an unsuspected esophageal diverticulum may also be noted by this means (Fig. 7). The examination of an esophagogram prior to an anticipated difficult pulmonary resection, especially a pleuropneumonectomy or a completion pneumonectomy, appears to be a wise precautionary measure. However, a normal esophagogram may give no clue to the presence of adhesions involving the esophagus, traction upon which may result in tenting of the esophageal wall and inadvertent injury to it during a difficult dissection. This resembles the mechanism more familiar to general surgeons doing gall bladder surgery, by which the common bile duct is tented up and inadvertently injured due to excessive traction on the cystic duct. Sauerbruch reports perhaps the earliest case of this type which involved a traction diverticulum.[5]

The probability that surgical trauma was involved is much more remote, however, in the remaining 17 patients, in whom symptoms and signs of a fistula appeared for the first time from 3 months to 6 years after operation. In these, some other cause must be sought.

In an attempt to arrive at a more adequate explanation for these late appearing fistulas, two other groups of patients were also studied. One group consisted of 33 tuberculous patients in whom an extrapleural-esophageal fistula developed following an extrapleural surgical procedure, such as extrapleural pneumonolysis, thoracoplasty, etc.[6-18] These were all in adults, most occurred on the right side, and most occurred in association with long-standing infection of the extrapleural space. The French medical literature was the richest source for these case reports, most of them being reported in the past 10 years. The

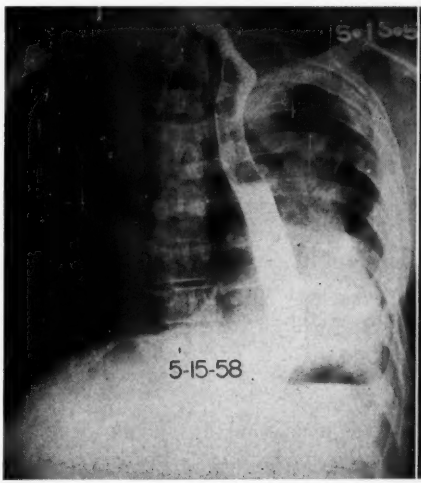

Fig. 6.

Fig. 7.

Fig. 6.—Unsuspected localized esophageal deviation toward area of chronic tuberculous disease in left upper lung field which was discovered by preoperative barium swallow. Patient later underwent a left pneumonectomy without complications.

Fig. 7.—Right anterior oblique view of traction diverticulum of mid-esophagus discovered 2 years after right pneumonectomy for bronchiectasis. This patient remains well 9 years following the resection.

approximate distribution of 27 of these fistulas is noted in Fig. 1, and data regarding them are summarized in Tables II and III. For convenience, these fistulas have been called Type II fistulas, to distinguish them from the first group, or those which followed largely intrapleural surgical operations.

Last, we were able to collect reports of 35 patients in whom an esophagopleural fistula was discovered associated with and apparently resulting from an intrapleural empyema, often of long duration (up to 14 years!).[19-51] Perhaps these might be more properly labeled pleuroesophageal fistulas. The majority were reported before the era of antibiotics, and largely in association with nontuberculous empyemas. In general, these patients were of a much

younger age group (more than half were under 20 years of age). The approximate site of esophageal perforation in 25 of these cases is indicated in Fig. 1. For convenience, we are calling these Type III fistulas (Tables II and III).

The common denominator in most late-occurring Type I fistulas, and in Type II and Type III fistulas was the presence of a pre-existing empyema, often of long duration. It was thought by many observers that these chronic pleural, extrapleural, or mediastinal empyemas, inadequately drained, were responsible for most fistulas not due to direct surgical trauma.

Fistula formation was believed to have occurred in many of all three types of cases as an empyema necessitatis, with rupture into the esophagus. Other significant possibilities mentioned were rupture into the pleural or extrapleural space of suppurating or caseating lymph nodes which had previously established communication with the esophageal lumen; or spread of pleuropulmonary disease (often tuberculosis) by contiguity; or rupture of a traction diverticulum of the mid-esophagus. Erosion of the esophagus by a hard drainage tube was also suggested.

Any of these mechanisms would help to explain the late appearance of some fistulas following the onset of pleural (or extrapleural) infection, and there is certain indirect evidence available to support each postulate.

The preponderance of fistula formation involving the right pleural cavity (75 per cent of the total number of all three types for which data were available) is explainable in part by the anatomy of the esophagus. On the right side, this organ is intimately associated with the mediastinal pleura, while on the left side it is separated from the pleura by the aorta through much of its course. Following extrapleural dissections, this organ would therefore be even more vulnerable on the right side to injury or infection or both, than it would on the left.

The occurrence of intense mediastinal lymphadenopathy in and about the carinal and subcarinal areas might also help to explain the localization of many fistulas at the mid-esophageal level. This is the level at which perforation of the esophagus by tuberculous lymph nodes has most commonly been noted,[52] and also at which bronchoesophageal and tracheoesophageal fistulas, as well as traction diverticula, most often occur.[53-58] The causative pathologic changes in the "middle lobe syndrome" are also located at this level. There are interesting case reports in which various combinations of these conditions, such as the "middle lobe syndrome," broncholithiasis, traction diverticula, and esophagorespiratory fistulas, have occurred in the same patient,[59-62] apparently linking them in a pathogenetic chain of events which may include, in some cases, the development of esophagopleural fistulas.

While there are isolated autopsy findings implicating caseous lymphadenopathy (Arandes Adan[6]) and traction diverticulas (McCormick,[37] Crawford[28] and possibly our Case 3) in the development of esophagopleural fistulas, in most cases pathologic data are so meager, and distortion of structures by long-standing infection and extensive fibrosis is so thorough, that the true pathogenesis of many chronic esophagopleural fistulas remains obscure.

The treatment of esophagopleural fistulas of whatever cause is complicated and unsatisfactory. Nevertheless, every attempt should be made to maintain nutrition, eliminate infection, obliterate empyema spaces, and restore function if possible. Extensive esophageal reconstructive procedures such as bowel transplants proved to be fatal in every case of Type I fistula. Haight's* patient, with a Type II fistula (following a thoracoplasty), recovered after colon transplant, a healing empyema drainage tract remaining. In most cases, more conservative operations on the chest wall (Schede thoracoplasty, muscle flap) or on the mediastinum or esophagus (direct closure, or excision and reanastomosis of the esophagus), while often not curative, were at least considerably safer. Jejunostomy for the maintenance of nutrition was much more satisfactory than gastrostomy, or even tube feedings, because regurgitation of stomach contents through the fistula was thereby avoided. In those patients in whom no definitive surgical therapy (other than gastrostomy or jejunostomy) was done or was possible, the mortality rate was 90 per cent.

SUMMARY AND CONCLUSIONS

Esophagopleural fistula is an uncommon but not rare complication of thoracic surgery, especially of the surgery of pulmonary tuberculosis. Four cases were observed in 934 pulmonary resections for tuberculosis. Twenty-nine additional cases following intrapleural procedures were contributed for this study by surgeons in many parts of the United States and India and these were compared with 33 cases of esophagopleural fistulas following extrapleural thoracic surgical procedures, such as thoracoplasty and extrapleural pneumonolysis. In addition, a group of 35 cases of benign esophagopleural fistulas following empyema, not associated with a prior thoracic surgical procedure, was also analyzed.

Fistulas which appeared soon after operation (within 3 months) were thought to be due most often to surgical trauma, while those which appeared late (from 3 months to 8 years following surgery) were thought to be due to chronic infection. The exact sequence of events by which perforations of the esophagus were brought about was often obscure.

Treatment has been in general unsatisfactory and the mortality and morbidity rates were high. Suggested preventive measures include preoperative esophagograms to detect unusual deflections or unsuspected diverticula of the esophagus, and prompt and vigorous obliteration of postoperative infected spaces. The gravity of this complication is emphasized by the over-all mortality rate of 51 per cent.

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THE SURGICAL TECHNIQUE FOR THE CORRRECTION OF PECTUS EXCAVATUM

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SINCE the appearance of Brown's paper in 1939[1] on the surgical treatment of pectus excavatum, or funnel chest, thoracic surgeons have shown a lively interest in this deformity.

It is now generally accepted that, when surgical correction is indicated, some type of the so-called radical operation is indicated. Various writers have outlined a number of techniques for this operation and, in general, they differ little.[2-6] These differences have principally been concerned with the method of external maintenance of the refashioned chest wall. While external struts or ladders, or internal fixation by pinning were almost universally performed a few years ago, the trend has been to modify or discard their use.[7]

We should like to present our technique which is a further modification and, we believe, a significant improvement for two reasons. In the first place, the one universally accepted indication for operative correction of funnel chest is the cosmetic one. Our operation is designed to effect a more nearly perfect cosmetic result than those previously described. In the second place, paradoxical movements of the sternum and chest wall are eliminated by solid fixation without the necessity of internal or external struts.

TECHNIQUE

Intratracheal anesthesia is employed with the patient supine on the operating table. In males, a midline sternal incision is employed, whereas in females, a transverse submammary incision is used. The midline incision is easier and gives better exposure but admittedly often results in scars which tend to widen. The skin incision begins at the cephalad end of the depression and is carried downward to a point midway between the xiphoid cartilage and the umbilicus (Fig. 1). Next, the pectoral muscles and their fascia are separated by sharp dissection from the underlying sternum and costal cartilages. This stripping is carried from the midline laterally to slightly beyond the costochondral junctures. The depression invariably begins medial to these junctures.

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The anterior rectus fascia is then divided and the two rectus muscles are separated through the full extent of the skin incision. Care is taken not to enter the peritoneal cavity during this maneuver. The origins of the two rectus muscles are freed from the lower costal margins and xiphoid process, and turned laterally as seen in Fig. 1. The xiphoid process is usually excised to facilitate this maneuver.

At this point, T incisions of the periosteum are made at the costochondral junctures. The periosteum is stripped with a small periosteal elevator to expose the most lateral 2 cm. of the costal cartilages. These exposed 2 cm. of cartilage are resected and discarded. The resections are begun at the lower costochondral junctions and are carried upward to the level of the beginning of the sternal depression which usually includes the third costochondral junction.

By blunt dissection with a peanut dissector, the diaphragm is freed from the posterior wall of the body of the sternum. We have been impressed that very little fibrous connection is found between the xiphoid-sternum and the diaphragm. Next, the intercostal bundles are divided between the resected cartilages so that the entire breast plate is attached above only through the body of the sternum. The anterior plate of the sternum is then divided transversely with an osteotome just above the level where the sternal depression begins. This is usually at the third intercostal space. The entire freed breast plate is elevated until the posterior plate of the body of the sternum is cracked. The freed breast plate then resembles a pair of wings (Fig. 2) with a central depression.

The freed sternum and attached portions of cartilages and intercostal muscles are fashioned to produce a perfectly flat contour by multiple cuts. These cuts are made transversely through the costal cartilages in as many places as necessary to remove all depressions. Since the sternum itself almost invariably has a central depression, it must also be flattened to effect a perfect cosmetic result. This is accomplished by multiple longitudinal and transverse sectionings of its anterior plate, after which the posterior plate is broken by hyperflexion of the sternum. The number of these transections of both the sternum and the costal cartilages varies in each case, depending upon the severity of the deformity and the age of the patient. In a child the sternum can be cut with an osteotome. In adolescent and adult patients we use an electric Stryker saw to cut the sternum. The costal cartilages can always be cut with a knife. Fig. 2, *a* shows the costal cartilages being cut. After these multiple cuts, the sternum and attached costal cartilages have the appearance of diced bone and cartilage held together by fibrous tissue and intercostal muscle.

After the sternal plate has been flattened, it occupies a wider area than the space from which it came. The excess cartilage and intercostal tissue is excised with a scissors so that the free plate will fit into the created defect. In Fig. 2, *a* the areas lateral to the dotted lines represent the portions of cartilage and intercostal tissue to be excised and discarded. We cannot overstress the importance of being careful to eliminate all sternal and costal depressions, as this is the secret of a good cosmetic result.

The flattened, trimmed, diced plate is fitted back into its space, but it will now be noted that it rides higher and that the costal cartilages do not necessarily meet with their previous costal counterparts (Fig. 3). Several of the lower ribs will not have any cartilages adjoining them.

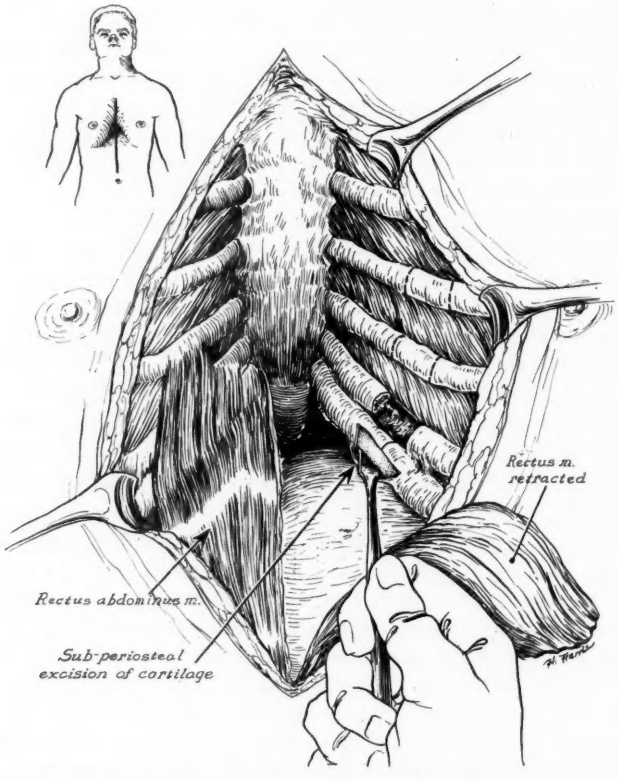


Fig. 1.—The reflection of the freed recti muscles is shown, as well as the resection of segments of cartilage, at the costochondral junctions. Inset shows the extent of the skin incision.

The plate is anchored firmly in place by interrupted sutures between intercostal muscles and costal cartilages. These sutures vary in number depending on whatever seems to be necessary to produce a completely stable chest wall. As shown in Fig. 3, *a*, several stabilizing sutures are also taken in the transected sternum at its top.

The rectus muscles are brought together in the midline by interrupted sutures through the anterior rectus fascia. The rectus muscles are not attached to the costal margin in order to avoid drawing the sternum down again. A defect then remains between the approximated rectus muscles and the xiphoid area. This defect causes no later herniation as it is supported posteriorly by

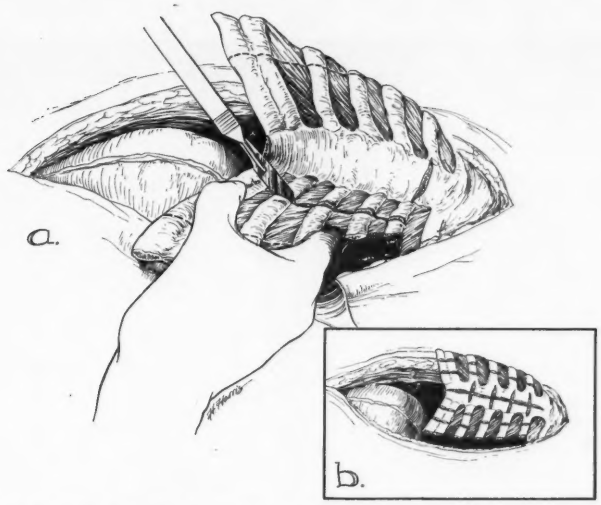


Fig. 2.—*a*, Note the winged appearance of the freed sternum and attached costal cartilages. The beginning of multiple transections of the cartilages is shown. The dotted lines indicate the portions of cartilage and intercostal muscle to be excised.

b, The appearance of the breast plate after multiple cuts of the sternum and cartilages have been made. The excess cartilage has also been excised.

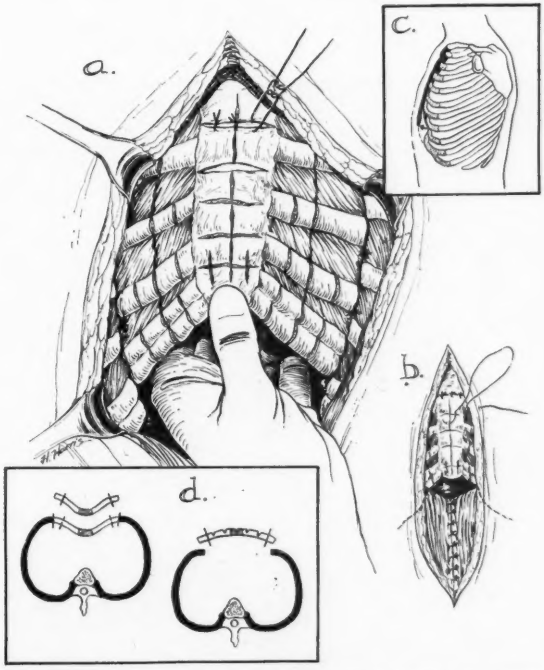
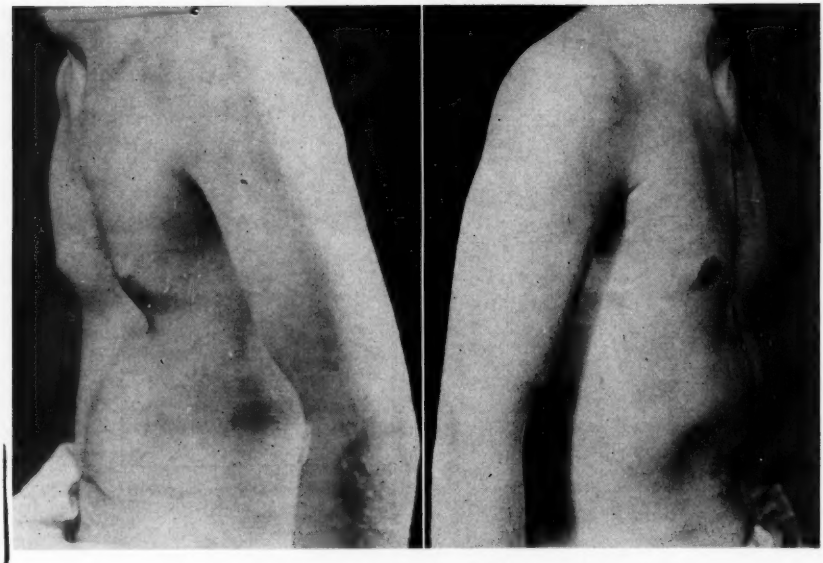


Fig. 3.—*a*, The refashioned breast plate is shown fixed in its new position by interrupted sutures. Note that the costal cartilages now do not necessarily meet the ribs.

b, The rectus fascia has been joined in the midline by interrupted sutures. The first suture joining the pectoral fascia is being inserted and is shown passing through the periosteum of the body of the sternum.

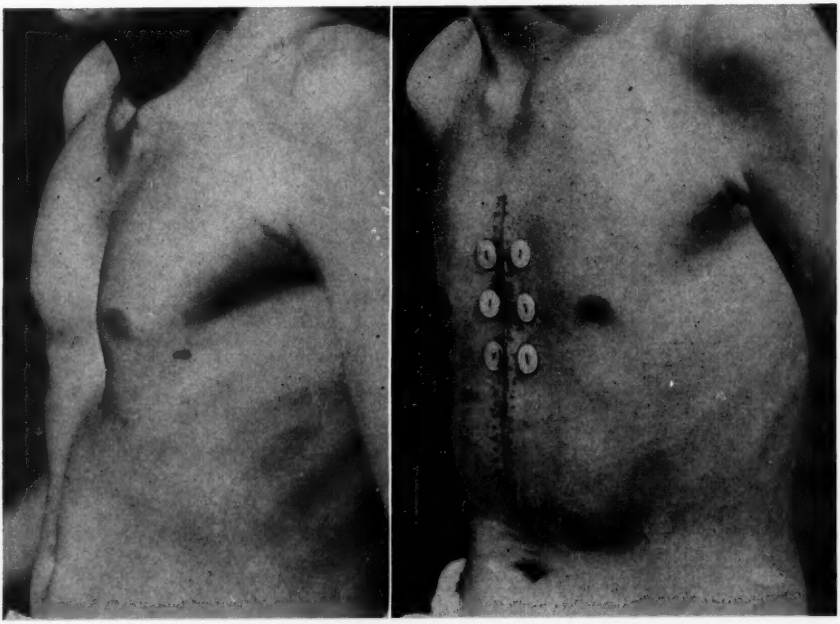
c, A lateral view showing the new position of the sternum.

d, Horizontal body section showing the method of overcorrection of the breast plate by multiple transections and final trimming.



a. *b.*

Fig. 4.—*a*, The appearance of a 17-year-old boy before operation for funnel chest. *b*, The appearance of the same patient after operation for funnel chest.



a. *b.*

Fig. 5.—*a*, The appearance of a 15-year-old boy before operation for funnel chest. *b*, The appearance of the same patient after operation for funnel chest showing retention sutures over buttons still in place.

the diaphragm. The pectoral fascia is brought together by interrupted sutures, taking a bite also in the midline periosteum of the body of the sternum with each suture (Fig. 3, *b*).

In dividing the intercostal muscles, the pleura is usually entered on at least one side and often on both sides. If a small pleural hole is produced, it is closed. But a large opening is always left in one pleural cavity so that the retrosternal drainage can run into this pleural cavity. A chest tube, connected to an underwater-seal, is brought out of this chest cavity through a separate stab wound lateral to the breast.

The skin is reapproximated with interrupted sutures. When a midline incision is employed, three or four wire-retention sutures are placed in the skin tied over buttons in an effort to prevent tension and subsequent widening of the scar.

The chest tube is removed the next day. The patient is usually allowed out of bed in several days. Children appear to tolerate the pain of the procedure better than adults. The patient is discharged home between the eighth and tenth postoperative day. The wire-retention sutures are removed in 2 weeks. Strenuous activity is restricted for several months. Figs. 4 and 5 demonstrate the results obtained using the described method on two adolescent patients.

SUMMARY

A modified technique for the radical repair of pectus excavatum is presented. We feel that this technique effects a more nearly perfect cosmetic result than previously described methods. In addition, it offers greater stability of the chest wall without the necessity of internal or external struts.

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MYOCARDIAL NECROSIS FOLLOWING ELECTIVE CARDIAC ARREST INDUCED WITH POTASSIUM CITRATE

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ELECTIVE cardiac arrest, induced in the course of open cardiac operations with cardiopulmonary bypass, has been found to be a valuable technical adjunct. In particular, the quiet and dry field it provides greatly facilitates the repair of the more complex anomalies. Of the various methods available for producing elective asystole, the technique devised by Melrose[1] has been most widely employed. In this technique, the heart is arrested by the injection of a solution of potassium citrate into the ascending aorta, proximal to an occluding clamp. This method of arrest was often employed at the National Heart Institute and its advantages seemed clear. Sometimes, however, difficulty was encountered in re-establishing effective myocardial contraction and an occasional patient presented clear evidence of left ventricular failure in the post-arrest period. These observations suggested a physiologic evaluation of the effects of potassium citrate on myocardial function.[2] The hearts of 2 patients who died after potassium citrate arrest revealed, on routine histopathologic study, unusual areas of necrosis and prompted a detailed pathologic re-examination of the hearts of all patients who died following open cardiac operations. The results of these studies in 30 patients are described in the present report.

MATERIALS AND METHODS

Material available for the study consisted of the hearts of 30 patients who had died at various intervals following direct vision intracardiac operations. Nineteen patients had had elective cardiac arrest induced with potassium citrate. In none of the remaining 11 patients had this technique been employed; in 9 no form of arrest was used and arrest was induced in 2 by aortic occlusion alone. In every patient, total cardiopulmonary bypass was provided by either a modified Melrose pump-oxygenator (12 patients) or a rotating disc oxygenator with a nonocclusive roller pump (18 patients). Systemic flow was, in general, provided at a rate of 2 L. per minute per square meter of body surface area and the duration of perfusion varied from 9 to 113 minutes.

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When elective arrest with potassium citrate was induced, a solution of 2.5 per cent potassium citrate was prepared by diluting a 25 per cent solution with nine volumes of fresh, heparinized blood. The aorta was cross-clamped immediately distal to the heart and the arresting solution was injected as rapidly as possible into the aortic segment until complete myocardial paralysis was observed. Following completion of the intracardiac procedure, coronary flow was restored by removal of the aortic clamp. In all instances the right heart was drained during the recovery period to prevent distention. The periods of aortic occlusion ranged from 6 to 67 minutes.

Routine pathologic examination of the hearts of these 30 patients had been made at the time of autopsy and they had been fixed in formalin and stored. They were re-examined grossly and full-thickness sections were prepared from blocks taken from the anterior wall, posterior wall, and apex of the left ventricle as well as from the ventricular septum and the wall of the right ventricle. Additional sections of both coronary arteries were also studied. Although these various sections were taken from pre-determined places in the ventricles, care was taken to avoid the surgical incisions or other obviously traumatized areas.

RESULTS

A distinctive type of necrosis was observed in various portions of the myocardium in the hearts of 15 (79 per cent) of the 19 patients subjected to potassium citrate arrest. The distribution and severity of the necrotic myocardial lesions, together with pertinent clinical data, are presented in Table I. This lesion was not observed in any of the hearts of the 11 patients who did not receive potassium citrate at the time of intracardiac surgery.

Characteristically the lesions consisted of multiple, sharply circumscribed, microscopic areas of necrosis which usually occurred in the central portion of the ventricular myocardium. Their appearance is shown, at various magnifications, in the representative photomicrographs reproduced in Figs. 1 through 5. The necrotic fibers were swollen and stained intensely with eosin. The cytoplasm in these fibers was either hyalinized or granular and neither cross striations nor longitudinal fibrils could be seen. The nuclei were large and stained strongly with hematoxylin. Even in the acute lesions, those observed in patients who died 2 hours or less after cardiac arrest, there was already disintegration and dissolution of portions of the necrotic fibers and granular debris could be seen between the larger, intensely stained fragments. A striking feature of the lesions was the absence of both hemorrhage and congestion. The cut surface of the myocardium in those hearts exhibiting the largest and most diffuse lesions was grossly dark and discolored. This darkened, mottled appearance was more pronounced in the central portions of the myocardium and often the subendocardial zone was quite pale. The over-all appearance followed closely the distribution of the lesions as shown in Figs. 1 and 2.

The amount of myocardial necrosis varied from single isolated microscopic areas observed in one histologic section, to massive necrosis, involving as much

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TABLE I. CLINICAL SUMMARIES AND PATHOLOGIC FINDINGS IN PATIENTS SUBJECTED TO CARDIAC ARREST WITH POTASSIUM CITRATE

PATIENT AND NUMBER	AGE (YR.)	SEX	DIAGNOSIS	DURATION OF CARDIO-PULMONARY BYPASS (MIN.)	DURATION OF ARREST (MIN.)	VOLUME OF 2.5% K CITRATE (C.C.)	DURATION OF LIFE AFTER ARREST	DEGREE AND DISTRIBUTION OF MYOCARDIAL NECROSIS*			
								LVA	LVP	SEP-TUM	RV
1. E. R. (01-59-24)	1½	M	Ventricular septal defect	20	10	50	4 hr.	0	0	0	+
2. D. Y. (01-62-55)	25	F	Ventricular septal defect	34	25	40	5 da.	0	++	+	0
3. P. L. (01-53-77)	5	F	Atrial septal defect and ventricular septal defect	43	22	20	2 hr.	++	0	+	0
4. J. P. (01-74-95)	13	F	A-V canal	28	20	40	26 da.	0	0	0	0
5. W. G. (01-81-62)	42	M	A-V canal	33	20	60	16 hr.	++	++	+++	+
6. L. M. (01-81-69)		M	Tetralogy of Fallot	75	30	60	None	0	0	+	0
7. N. A. (01-68-78)	6	F	Ventricular septal defect	18	6	60	28 hr.	0	0	0	0
8. H. W. (00-85-09)	22	M	Tetralogy of Fallot	31	24	60	48 hr.	0	0	0	0
9. J. K. (01-91-66)	4	F	Ventricular septal defect	26	15	20	1½ hr.	++	0	0	+
10. D. S. (00-80-73)	2	M	Ventricular septal defect	30	15	20	28 hr.	0	0	0	0
11. D. Y. (00-88-77)	4	F	Ventricular septal defect	26	13	20	24 hr.	+	0	0	0
12. M. P. (01-94-08)	6	M	Ventricular septal defect	26	20	60	16 hr.	++++	++++	++++	++
13. S. D. (00-93-72)	39	F	Congenital aortic stenosis	25	15	30	10 da.	++++	++++	++++	+
14. R. I. (00-99-66)	8	M	Ventricular septal defect	36	15	30	2 hr.	++++	++++	++++	0
15. A. W. (00-98-42)	7	M	Tetralogy of Fallot	46	15	?	12 hr.	+	0	+	0
16. E. B. (01-85-33)	18	M	Supravalvular aortic stenosis	113	67	90	None	+++	+++	+++	+
17. D. F. (01-83-98)	10	M	Congenital aortic stenosis	25	12	27	12 hr.	++++	++++	++++	+
18. L. B. (00-95-07)	8	M	Tetralogy of Fallot	59	24	30	16 hr.	0	++	0	++++
19. M. D. (02-25-37)	4	F	Tetralogy of Fallot	41	16	25	28 hr.	0	+++	0	+

*LVA = anterior wall of left ventricle; LVP = posterior wall of left ventricle; RV = right ventricle.

as 50 per cent of the myocardium, seen in several sections. These degrees of necrosis were designated as + to ++++ in the various sections examined and their distribution in the anterior wall of the left ventricle (LVA), posterior wall of left ventricle (LVP), ventricular septum and right ventricle (RV) is shown in Table I. The lesions were severe (+++ to ++++) in 6 patients, moderate (++) in 2 patients and mild (+) in 7 patients. No lesions were found in the hearts of 4 patients. It is evident from the data presented in Table I that the lesions were more severe in the left ventricle than in the right, although only one block from the right ventricle was examined.

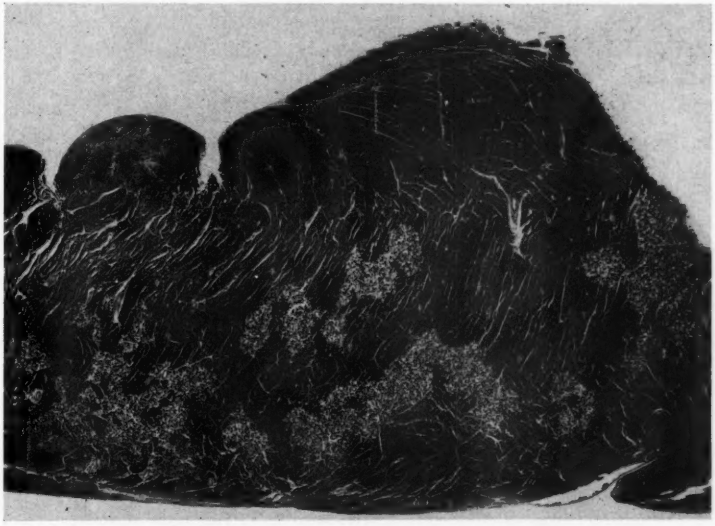

Fig. 1.—Patient No. 14 (00-99-66) was an 8-year-old boy with ventricular septal defect who died 2 hours after potassium citrate arrest. Multiple, discrete areas of necrosis in the midportion of the wall of the left ventricle can be seen. Some of the lesions are confluent. Characteristically these lesions were neither hemorrhagic nor congested. (Hematoxylin and eosin; ×8; reduced ⅙.)

Sections of both the right and left coronary arteries were examined in each heart. The degree of atherosclerosis varied from patient to patient but did not appear to correlate well with either the severity or distribution of the myocardial lesions. Thrombosis or necrosis of coronary arteries was not observed to be associated with any of the lesions. The atria were not examined systematically but a portion of the left atrium was usually included in the block taken from the posterior wall of the left ventricle and necrosis was never observed in it.

In the second group of 11 patients, cardiopulmonary bypass had been employed at the time of intracardiac surgery but cardiac arrest was either not induced (9 patients) or was produced by aortic occlusion alone (2 patients). The anatomic defects necessitating operation and the conditions of perfusion were comparable to the patients listed in Table I. No necrotic myocardial lesions of the type just described were seen in sections of these hearts. Indeed, the only pathologic changes noted were those specifically associated either with the defect

for which operation had been performed, with the operative incisions themselves, or the small areas of acute hemorrhage and edema which follow cardiac massage and defibrillation.[3] In most instances, the myocardium appeared normal.

DISCUSSION

The patients are arranged in chronologic order according to the date of operation in Table I. It is apparent that the most severe lesions were encountered in Patients 12 to 19 and less severe lesions were seen in Patients 1 to 11. All 4 of the patients who received potassium citrate but whose hearts did

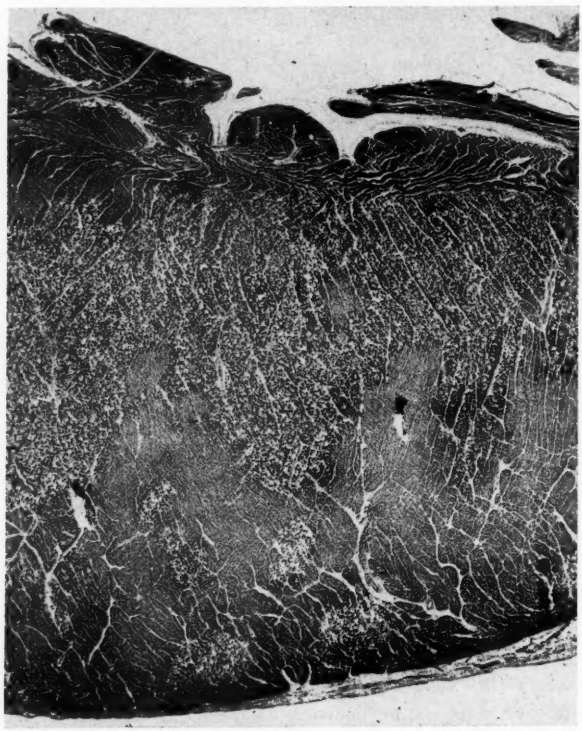

Fig. 2.—Patient No. 17 (01-83-98) was a 10-year-old boy with congenital aortic stenosis who died 12 hours after cardiac arrest with potassium citrate. The massive, confluent areas of necrosis involve more than half of the myocardium of the left ventricle. Note, as in Fig. 1, that the subendocardial and subepicardial layers of the myocardium tend to be spared. (Hematoxylin and eosin; ×100; reduced ⅙.)

not exhibit necrotic lesions were among the first 11 patients in the table. The date dividing these two groups was May, 1958, and re-examination of the surgical records shows that at this time a change was made in the pharmaceutical preparation of the 25 per cent potassium citrate stock solution. Before this date the solution was prepared in bulk and often had been stored in glass several months before it was used. However, precipitates were noted to form in the solution and flaking of the glass containers was observed. After May,

1958, the potassium citrate was furnished in crystalline form and the 25 per cent solution was prepared by adding a measured amount of diluent to a weighed quantity of the crystals immediately before use. Following this change in the procedure for the preparation of the potassium citrate solution, every patient who died after potassium arrest had myocardial necrosis. The lesion, in fact, was severe in the hearts of 7 of the 8 patients. It thus seems likely that the drug, when freshly prepared from crystals, resulted in a more toxic solution which was responsible for more severe myocardial damage.

The data presented do not allow a conclusive statement as to the pathogenesis of the myocardial lesions; they were, however, unequivocally associated with perfusion of the heart with potassium citrate. There was no correlation between the occurrence of the myocardial necrosis and the type of congenital defect, the heart size, age, sex, or any other clinical factor that was considered. It is also remarkable that the occurrence and severity of the myocardial lesions do not correlate well with the amount of potassium citrate infused into the coronary arteries, the length of perfusion, or the duration of cardiac arrest. The association of more severe myocardial damage with the change in the preparation of the potassium citrate solution also indicates that the myocardial lesions resulted from its use. Recent experimental work lends further support to this conclusion. Waldhausen and his co-workers[2] showed, in a comparison with acetylcholine and anoxia as arresting agents, that potassium citrate caused severe depression of left ventricular function. Gilbert[4] has demonstrated that the distribution of the potassium citrate solution in the myocardium is by no means uniform and this observation poses the problem as to whether the necrosis occurs in areas which have or have not received the highest concentration of potassium citrate.

After the present study was initiated, Helmsworth and his associates[5] described histologically similar lesions in the hearts of dogs sacrificed 48 hours after cardiac arrest had been induced with potassium citrate. The lesion has also been produced experimentally in the dog in our laboratory and is remarkably similar to the lesions observed in the human being (Fig. 6). This experimentally produced lesion is also remarkable because the profound pathologic changes in the myocardial cells occurred within 30 minutes after perfusion with potassium citrate. Fully developed lesions were also observed within 1 to 2 hours in several of the patients in the study. Older lesions in the patients, lesions observed in patients who died 2 days or longer after operation, exhibited infiltrates of leukocytes and macrophages but were otherwise quite similar histologically to the acute lesions. The myocardial lesions produced by the potassium citrate appear to be distinctive. Study of the fresh lesions in the dog heart suggest that segments of the myocardial fibers have undergone acute disintegration leaving swollen and intensely staining remnants which are widely separated. Capillaries, small arterioles, and connective tissues within the lesion appear to be unaffected. These various features distinguish this lesion from a variety of other types of myocardial necrosis such as occur in acute infarcts,[6] in association with potassium deficiency,[7] or with noradrenalin.[8]

A discussion of the clinical course of patients with widespread myocardial damage of the type described is difficult since in some it was altered or obscured

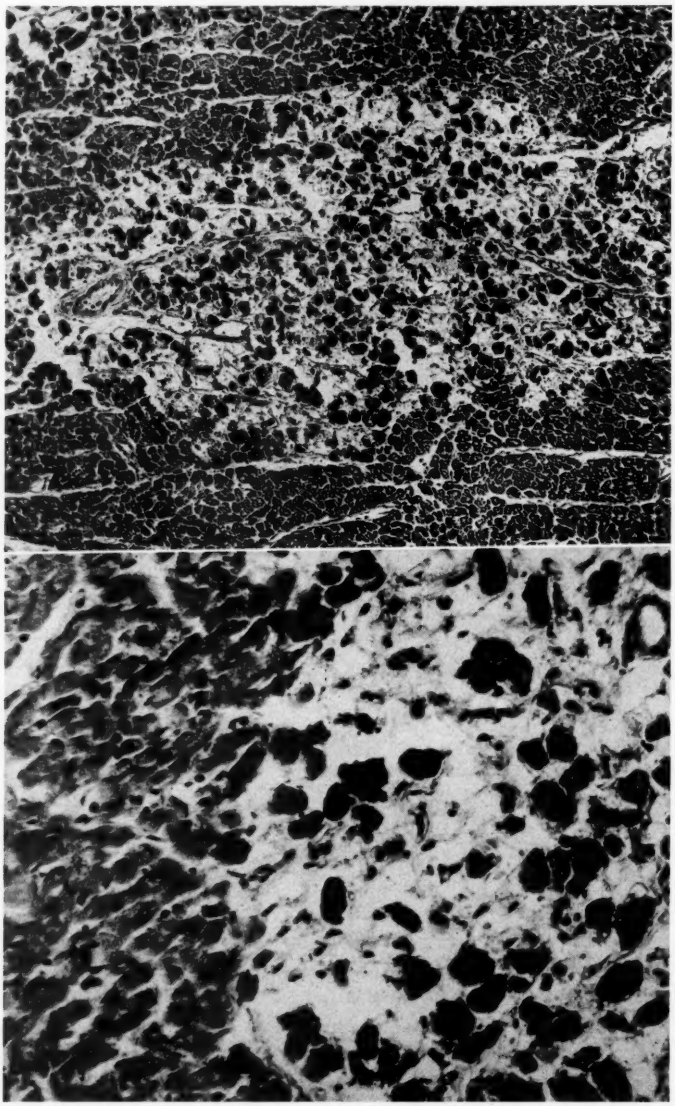

Fig. 3.—Same patient as in Figs. 1 and 4. This photomicrograph of a single lesion illustrates the discrete, sharp boundary between the area of necrosis and adjacent, normal myocardium. Many portions of the necrotic myocardial fibers have disintegrated and disappeared so that the remaining portions of the myocardial fibers appear widely separated. The thin-walled, intramural artery toward one end of the lesion has a normal appearance and its lumen is empty. The capillary-sized vessels are prominent because of the altered myocardium but they also appear normal and are free of thrombus. The lesion is not hemorrhagic. (Hematoxylin and eosin; ×100; reduced ⅙.)

Fig. 4.—Same patient as shown in Figs. 1 and 3. The portions of necrotic myocardial fibers which remain in the lesions are enlarged and stained intensely with eosin. The cell nuclei are enlarged and stained heavily with hematoxylin. Fragments of disintegrated fibers can be seen between the swollen fibers, but many portions of the injured fibers have dropped out. (Hematoxylin and eosin; ×275; reduced ⅙.)

by other significant factors such as postoperative hemorrhage or an incomplete anatomic repair. In others, however, death could clearly be attributed to the left ventricular failure which followed arrest. In these patients gradually

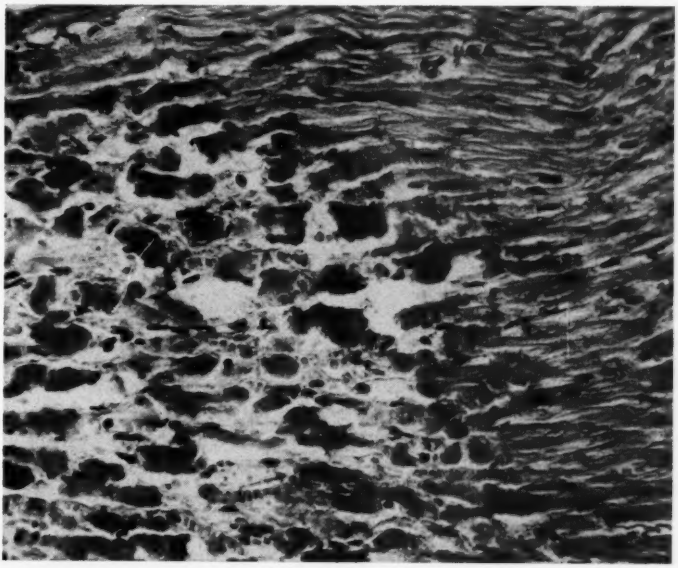

Fig. 5.—Patient No. 12 ((01-94-08) was a 6-year-old boy who died 16 hours after arrest with potassium citrate and repair of ventricular septal defect. The junction between normal appearing myocardial fibers and necrotic fibers is quite sharp. Fragmentation and dissolution of portions of necrotic fibers is apparent. (Hematoxylin and eosin; ×275; reduced 1/6.)

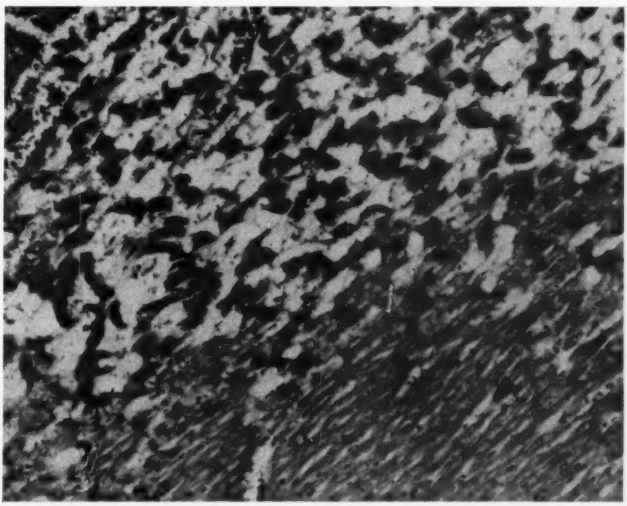

Fig. 6.—The histologic appearance of necrotic lesions in the dog heart after cardiac arrest with potassium citrate. The lesion is similar to that observed in patients. The animal was sacrificed 15 minutes after normal heartbeat was restored. (Hematoxylin and eosin.; ×100; reduced 1/6.)

progressive hypotension was observed which became unresponsive to pressor agents, and was associated with rising venous pressure. One patient (No. 13) apparently survived this acute period of failure, only to die 10 days after operation of an unrelated cause.

The clinical and pathologic observations just described and the experimental demonstration of impaired ventricular function following potassium citrate arrest has led to the abandonment of this technique at the National Heart Institute. Although flaccid paralysis of the heart certainly facilitates the repair of many intracardiac anomalies, the hazard of the method is so great as to outweigh this advantage. A dry and quiet field can be secured by intermittent aortic occlusion alone and this technique is applicable in virtually all procedures in which aortotomy is not necessary. When the aorta must be opened for long periods, as in the repair of aortic valve lesions, direct coronary perfusion has been found the technique of choice.

SUMMARY

Detailed microscopic examinations were made of the hearts of 19 patients who died at various intervals following open cardiac operations in which cardiac arrest had been induced by the infusion of potassium citrate into the coronary bed. In 15 (79 per cent) of the 19 patients, myocardial necrosis of a characteristic type was demonstrated. The lesion was not observed in the hearts of 11 patients who underwent similar procedures without arrest or with arrest produced by aortic occlusion alone. The etiology of the necrosis and its significance in the choice of an operative technique for clinical use is discussed.

ADDENDUM

Since the manuscript was submitted, detailed histologic study of the hearts of 7 additional patients has been made. In 4, anoxic arrest was employed and, in 3, the heart was not arrested. No evidence of myocardial necrosis was found in any section.

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DISSECTING ANEURYSM OF THE THORACIC AORTA AS A COMPLICATION OF CATHETER AORTOGRAPHY: SUCCESSFUL SURGICAL TREATMENT

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THE widespread use of translumber aortography which followed the original description of the method by Dos Santos and his colleagues[1] has resulted in numerous reports of complications of the procedure. Recent reviews of these complications have been written by Crawford and his co-workers[2] and McAfee and Willson.[3] In contrast, much less attention has been devoted to the complications of catheter aortography perhaps because this method has been applied much less often.

Abdominal aortography by injection through a catheter introduced by way of the femoral artery was first performed by Farinas.[4] Thoracic aortography by catheterization from the radial artery was described by Radner.[5] This method has been extensively applied with great success in Sweden.[6, 7] The sole complication in a large series of cases was a single mild cerebral injury which occurred following the injection of too high a concentration of opaque substance into the cerebral circulation as a result of incorrect placing of the tip of the catheter. Lane and Peirce[8] reported brachial plexus palsy following extravasation of 70 per cent Diodrast injected through a polythene catheter in an effort to demonstrate an innominate artery aneurysm. Deterling[9] reported the occurrence of cerebral complications presumably resulting from the dislodgment of an atheromatous plaque by a catheter introduced into the aorta from the left ulnar artery.

Dissection of the aorta during the performance of a catheter aortogram has not been reported but the occurrence of this complication with percutaneous translumber aortography is recognized. In an excellent discussion of this problem, Gaylis and Laws[10] presented 2 cases of their own with photographs demonstrating dissection of the abdominal aorta and discussed 5 cases in the literature which they considered similar. More recently, Fineberg and associates[11] reported the occurrence of gangrene of the large intestine and ovaries due to dissection of the abdominal aorta after translumber aortography. This

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complication of translumber aortography results when all or a portion of the bevel of the needle lies in the wall of the aorta so that the opaque material is injected either entirely or in part into the aortic wall.

The purpose of this paper is to report the occurrence of a dissecting aneurysm of the thoracic aorta as a complication of catheter aortography and its successful treatment by excision and replacement with a Dacron prosthesis.[12]

CASE REPORT

The patient, a 60-year-old salesman, was admitted to Jefferson Medical College Hospital on Nov. 18, 1958. He had consulted his local physician because of epigastric distress and a pulsating mass had been found in the upper abdomen. Roentgenograms had confirmed the presence of an abdominal aortic aneurysm and demonstrated an active duodenal ulcer. Except for the complaints associated with the duodenal ulcer, the patient's general condition had been satisfactory, although the electrocardiograms had shown evidence of arteriosclerotic cardiovascular disease.

Physical examination was not remarkable except for the presence of the pulsating epigastric mass. The location of the aneurysm, both on physical examination and on the scout films of the abdomen, raised the question as to whether or not it arose far enough proximally to involve the renal arteries. For this reason a catheter aortogram was performed on Nov. 21, 1958. Under local anesthesia, the left ulnar artery was exposed in the left forearm. A No. 8 cardiac catheter was introduced proximally through the artery into the aorta and advanced easily until the tip lay above the diaphragm. Blood flowed from the end of the catheter under pressure but the pulsation was dampened. The catheter was connected to an automatic pressure injector and 30 ml. of 50 per cent Hypaque was injected while a series of x-ray films were exposed. With the injection of the contrast medium the patient cried out loudly, complaining bitterly of severe tearing pain in the back. Following removal of the catheter the pain subsided and became less severe. His general condition was found to be satisfactory and the blood pressure was normal. There was mild elevation of the pulse rate. The femoral pulses were quite normal. Examination of the roentgenograms revealed the presence of dissection of the descending thoracic aorta resulting from the injection of the contrast material between the layers of the wall of the aorta above the diaphragm (Fig. 1). The appearance was that of complete aortic obstruction. A subsequent film taken 30 minutes later showed that all of the dye in the aorta had disappeared and that there was an excellent concentration of dye in the urinary bladder, attesting to the preservation of renal blood flow (Fig. 2). An x-ray film of the chest showed no change in the cardiac and aortic silhouette from that observed on admission (Fig. 3).

Pain in the back, however, continued and it was decided that operative repair of the dissection of the thoracic aorta should be performed. Hypothermia was induced by external cooling until a low temperature of 29° C. was attained 4 hours after the dissection. With the patient on the right side a left posterolateral thoracotomy was performed at the fourth interspace. The wall of the aorta was discolored with extravasated blood from the origin of the subclavian artery to the diaphragm and its pulsations were diminished. The upper portion of the descending aorta and the distal portion of the arch were mobilized. Clamps were placed across the aorta proximal to the origin of the left subclavian artery and in the mid-thorax and the aorta was transected. The dissection was found to involve about two-thirds of the diameter of the vessel, beginning at the origin of the left subclavian artery. On the lesser curvature of the aorta, opposite the origin of the left subclavian artery, were several atherosclerotic ulcerated areas in the intima. A ten centimeter length of the aorta, including these ulcerated areas, was excised and replaced with a pre-clotted knitted Dacron prosthesis. The false lumen was excluded both proximally and distally by suturing both layers of the aorta together to the prosthesis. The clamps were removed and the circulation restored. The immediate condition of the patient was satisfactory. Three days later a tracheostomy was performed to facilitate the removal of retained secretions from the

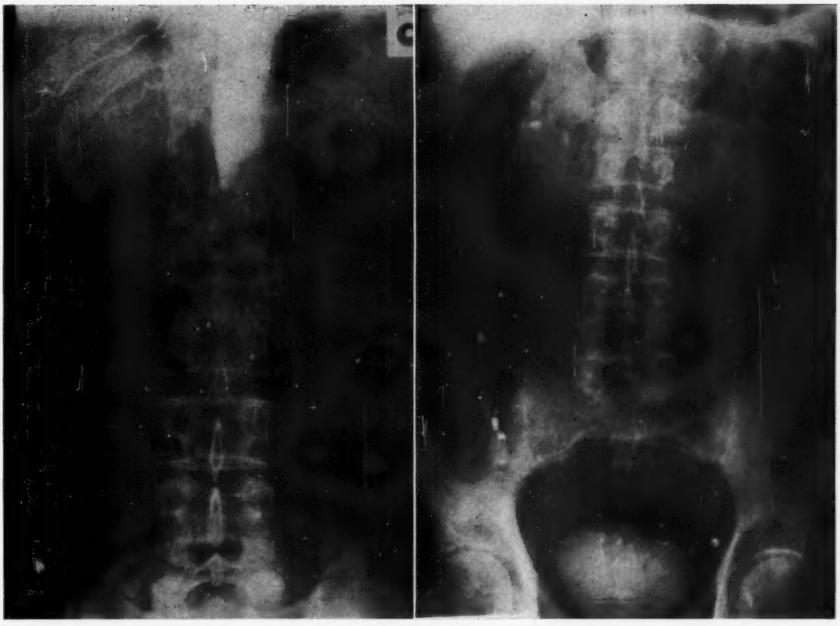

Fig. 1. Fig. 2.

Fig. 1.—X-ray film demonstrating radiopaque substance within the aortic wall causing transient obstruction.

Fig. 2.—Disappearance of radiopaque substance from the aorta and dense concentration in the urinary bladder 30 minutes after injection.

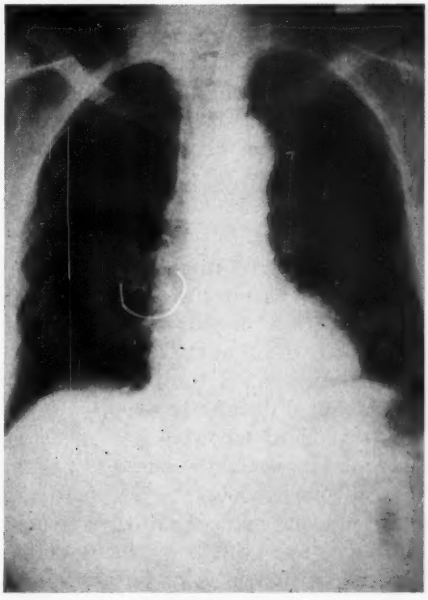

Fig. 3.—Normal contour of thoracic aorta 1 hour after injection.

tracheobronchial tree. At the same time, because of poor arterial flow to the left upper extremity, the left brachial artery, which had been utilized as a pathway for the introduction of the catheter, was explored and a thrombus removed from the artery distal to the origin of the profunda branch by retrograde flush. There was no evidence of dissection in the brachial artery.

Three weeks later the patient was operated upon for his arteriosclerotic abdominal aortic aneurysm. The aneurysm was found to be large and lobulated and to arise just distal to the renal arteries. The aorta, proximal to the aneurysm, was badly diseased but there was no evidence that dissection extended below the diaphragm. The aneurysm was excised and replaced with a knitted Dacron bifurcation prosthesis. [13] The patient made a satisfactory convalescence after the resection of the abdominal aortic aneurysm and was discharged from the hospital 12 days after the last operation.

When he was seen in follow-up examination 6 months later his general condition was satisfactory. However, there was evidence of marked impairment of arterial flow to the left upper extremity. No pulses were felt distal to the left subclavian artery and there was hypesthesia and limitation of flexion of the fingers of the left hand. X-ray examination of the chest was unchanged. The lung fields were clear and only minimal widening of the aorta superiorly was noted.

DISCUSSION

The normal appearance of the aortic silhouette shortly after the production of the dissection by injection of the dye is shown in Fig. 3. The presence of the opaque material between the layers of the wall of the aorta at the completion of the injection is shown in Fig. 1. There is a sharp, right border of the opaque substance with a less definite contour to the left. There is minimal filling of the branches of the thoracic aorta, and, apparently, a complete obstruction of the aorta just above the level of the diaphragm. The dampened flow of blood from the catheter, the occurrence of severe characteristic back pain at the time of the injection of the opaque substance, and the appearance of the film leave no doubt that the dissection occurred as a result of, and at the time of, the performance of the study. The contrast material apparently was promptly removed from its position between the layers of the aortic wall as indicated by its absence from the wall on the later film and the presence of normal femoral pulses shortly after the performance of the study. Also, there was excellent excretion of the material by way of the kidneys as indicated by its presence in the urinary bladder as shown in Fig. 2.

The dissection probably occurred in the following fashion. The conventional No. 8 Lehman catheter was introduced without complication from the ulnar artery to the aorta. As it passed from the origin of the subclavian artery across the aortic lumen the tip of the catheter impinged upon one of the ulcerated areas, noted at operation, in the intima of the lesser curvature of the aorta. It was then advanced distally between the layers of the aortic wall dissecting sufficiently so that blood following it could be obtained through the catheter (Fig. 4). Only mild discomfort was experienced by the patient at this stage. The dissection was completed by the injection of the radiopaque substance under considerable pressure by means of the automatic injector (Fig. 5). It was at this time that the patient experienced the classical severe tearing pain. The extent of the dissecting aneurysm is shown in Fig. 6 and the final result in Fig. 7.

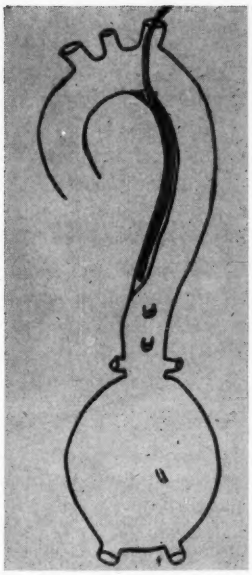

Fig. 4.

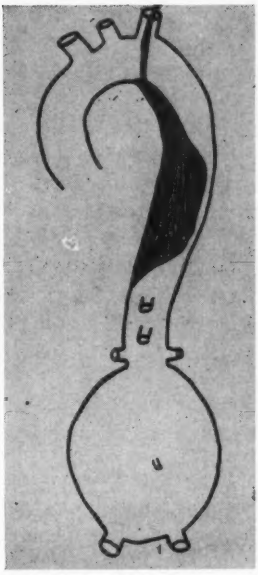

Fig. 5.

Fig. 4.—Passage of catheter through ulcerated area in the aortic wall.
Fig. 5.—Dissection produced by injection under pressure.

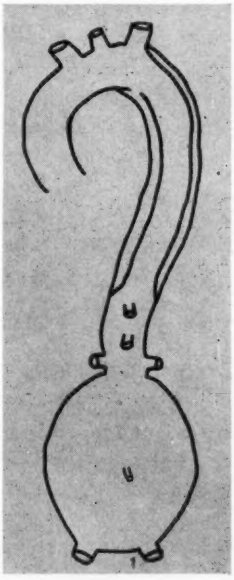

Fig. 6.

Fig. 7.

Fig. 6.—Extent of dissection.
Fig. 7.—Final result after excision and replacement of the source of the dissection, exclusion of the outer lumen proximally and distally, and resection and replacement of the abdominal aneurysm.

The poor prognosis of spontaneous dissection of the thoracic aorta and the continuation of pain in the back prompted the application of the operation for the control of dissecting aortic aneurysm described by De Bakey and his associates.[12] In this instance the location of the point of intimal perforation in an accessible area of the aorta distal to the proximal clamp permitted the performance of a curative type of operation with exclusion of the external lumen, both proximally and distally. The result achieved by this operation was such as to permit the patient to undergo successful resection of an abdominal aortic aneurysm 3 weeks later. The origin of the abdominal aneurysm distal to the renal arteries is in keeping with the characteristics of the great majority of these lesions.[2] The undesirability of performing diagnostic studies which are not necessary is obvious.

SUMMARY

The occurrence of a dissecting aneurysm of the thoracic aorta as a complication of a catheter aortogram has been described. The dissection probably occurred as the catheter tip penetrated an atherosclerotic ulcer of the intima. The aneurysm was successfully treated by excision and replacement with a knitted Dacron prosthesis. Subsequently an arteriosclerotic aneurysm of the abdominal aorta was replaced with a Dacron bifurcation prosthesis. Six months later the condition of the patient was satisfactory except for impairment of arterial flow to the left upper extremity.

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EXPERIMENTAL EXCISION OF PORTIONS OF THE LEFT VENTRICLE

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A LONG-TERM study of the effects of excision of portions of the left ventricle cannot be found in the literature. With the rapid advances in cardiovascular surgery, the excision of acute infarction is now an actuality, and such a study can act as a guide as to what to expect functionally and pathologically.

Excision of acute myocardial infarcts was advocated by Murray[1] on the basis of experimental evidence in dogs. The left anterior descending coronary artery was ligated proximal to the distal two or three large terminal branches over the mid-portion of the left ventricle. This produced a lowering of the blood pressure and cardiac output with rapid progressive heart failure. After excision of the involved myocardium, the heart failure regressed and many of the dogs lived for 1 to 2 years.

Bailey and Gilman[2] excised a larger portion of the infareted left ventricle by removing the segment involved by ligation of the left anterior descending coronary artery. All of these animals developed a heart failure syndrome similar to experimentally produced mitral stenosis. Of those surviving operation, 80 per cent died of heart failure. Carter and MacMillan[3] excised apical portions of the left ventricle in 25 dogs with 13 surviving for long-term study. There was no impairment of cardiac function or emboli in these animals.

The purpose of this study was to observe the effects on the heart of excision of portions of the left ventricle. As Bailey and Gilman's work showed a limitation in the amount of the left ventricle which could be excised, small areas were intentionally removed in order to obtain long-term survival for follow-up study.

METHODS

Mongrel dogs were used, varying in weight from 7.6 to 26.8 kilograms. Nembutal anesthesia was induced and the trachea intubated. A cuff on the endotracheal tube was inflated and carefully checked for leakage. The expired air was collected in Douglas bags after passage through a gas meter. Arterial

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blood samples were collected from a femoral artery catheter. A cardiac catheter was placed into the right ventricle through a femoral vein cut down, and was positioned by observing the right ventricular pressure curve on a Sanborn recorder. Expired air oxygen concentration was determined with a Beckman O_2 analyzer. Arterial and venous oxygen concentrations were determined by the method of Hickam and Frayser.[4] The cardiac output was then determined by the Fick principle.

After obtaining an initial cardiac output, the left side of the chest was opened and one of the large branches of the left anterior descending or left circumflex coronary artery was tied off. The area of cyanosis and paradoxical motion was observed and this outlined the area for excision. This usually amounted to an oblong area about 4 cm. long and 2 cm. wide. The surrounding normal-appearing muscle was approximated with mattress sutures of No. 1-0 chromic catgut on a large, curved, swaged-on needle. A continuous No. 1-0 silk arterial suture was then placed at the distal end of the puckered myocardium; as the myocardium was excised with small scissors, the continuous over-and-over suture was advanced. The pericardium was loosely closed, and the thoracotomy wound was closed in layers over a large catheter. The pleural cavity was aspirated well and the chest catheter was removed. Samples were then obtained for a repeat cardiac output. Subsequent determinations of cardiac output were done in a manner similar to the initial output.

An adequate depth of anesthesia was found to be necessary to prevent forceful expiration by the dog against the inflation phase of the respirator with loss of air from the system. Right ventricular samples were used instead of the pulmonary artery, since samples could seldom be withdrawn successfully from the pulmonary artery.

CLINICAL COURSE

Twenty-two dogs had an area of the heart excised which was made cyanotic by ligation of a branch of the left anterior descending coronary artery, and 10 dogs had an area of the heart excised after ligation of a branch of the left circumflex coronary artery. The causes of death are shown in Table I.

TABLE I. CAUSE OF DEATH OF 32 DOGS OPERATED UPON

	BRANCH OF LEFT ANTERIOR DESCENDING CORONARY LIGATED	BRANCH OF LEFT CIRCUMFLEX CORONARY LIGATED
Number of animals	22	10
Rupture of heart	6	1
Empyema	2	2
Atelectasis	3	0
Fibrillation at operation	3	0
Congestive failure	0	1
Aspiration pneumonia	1	1
Undetermined	1	1
Sacrificed	6	4

Nine dogs were operated upon as controls; 4 had a branch of the left anterior descending coronary artery ligated, and were observed to have an area of cyanosis and paradoxical motion; 5 dogs had a sham operation consisting of a left thoracotomy, opening of the pericardium, and manipulation of the heart, so that the time of operation was equivalent to the time necessary for excision of a portion of the myocardium.

Of the group which had a branch of the left anterior descending coronary artery ligated, 6 died of rupture of the heart between 4 and 12 days postoperatively. One of these dogs developed areas of skin necrosis from arterial emboli. Two dogs died of empyema on the fifth and fourteenth days; 3 of atelectasis on the first, second, and fourth postoperative day. Three dogs died at the time of operation from ventricular fibrillation. One dog died 2 months after operation from aspiration pneumonia following anesthesia for coronary arteriograms. One dog died 4 days after operation from an undetermined cause. Six dogs were sacrificed at 5, 6, 7, 12, 15, and 27 months after operation.

Of the group which had a branch of the left circumflex coronary artery ligated, 1 died of rupture of the heart 7 days postoperatively, and 2 died of empyema on the fifth and fourteenth days. One dog died of congestive heart failure 13 weeks after operation. This dog (C 27) had had a repeat cardiac output 1 day prior to death, at which time 4 L. of abdominal ascitic fluid were withdrawn. Autopsy showed mitral insufficiency due to the posterior papillary muscle being caught in the suture line. One dog (C 26) died 10 weeks after ventricular resection of aspiration pneumonia the day after a repeat cardiac output. One dog died on the first postoperative day of an undetermined cause. The remaining 4 dogs were sacrificed at 1, 2, 5, and 7 months.

The 4 control dogs, which had the branch of the left anterior descending coronary artery ligated, all did well after operation. One was autopsied at 3 weeks; 2 were autopsied at 4 weeks; and 1 was autopsied at 6 weeks.

The 5 control dogs which had sham operations did well after operation; 3 were not followed, and 2 were autopsied at 3 weeks.

TABLE II. CARDIAC OUTPUT IN LITERS PER MINUTE IN DOGS WHICH SURVIVED FOR REPEAT DETERMINATION*

DOG NUMBER	WEIGHT (KG.)	INITIAL	POSTOP.	2-3 WEEKS	4-6 WEEKS	8-13 WEEKS	20-28 WEEKS
C 10	10.0	2.7	1.5		2.6		
C 15	20.0	5.9	4.7		4.0		4.3
C 16	13.6	3.2	1.8	1.6			
C 20	21.1	5.4	1.8	3.0			4.5
C 23	26.8	7.1	2.4		2.7		4.2
C 25	19.1	4.5	2.7	1.5	3.5		2.9
C 26	7.6	0.6	0.4	2.0		3.1	
C 27	10.5	2.7	0.9		2.0	1.0	
C 28	20.9	5.6	1.4	1.6			
C 30	10.0	3.5	.7	3.0	1.8	5.6	
C 31	19.2	3.8	2.9	3.1		3.4	

*The first 5 dogs listed above had an area excised supplied by branches of the left anterior coronary artery and the subsequent 6 had an area excised supplied by branches of the left circumflex coronary artery. C 26 which was a young dog, grew during its period of observation from 7.6 Kg. to 14.5 Kg. C 27 also gained weight during its period of observation. This weight gain is accounted for by the fluid retention from congestive heart failure.

CARDIAC OUTPUTS

The data for the cardiac output findings in those animals which had them repeated at intervals after operation are shown in Table II.

The data for those dogs which had only a preoperative and immediate postoperative cardiac output done are shown in Table III. All but 4 of the 27 dogs with pre- and postoperative cardiac outputs showed a drop in cardiac output immediately after operation. A tendency was apparent for the cardiac output to increase with time after resection. In 1 case (C 27) congestive failure developed, and a subsequent fall in cardiac output was noted 13 weeks postoperatively. One dog (C 26) was a 7.6 kilogram puppy at the time of operation, and at the time of the last cardiac output weighed 14.5 kilogram. In this dog both subsequent cardiac outputs exceeded the initial level.

TABLE III. CARDIAC OUTPUT IN LITERS PER MINUTE IN DOGS WHICH DID NOT SURVIVE FOR REPEAT DETERMINATION

DOG NUMBER	WEIGHT (KG.)	CO L./MIN. (INITIAL)	CO L./MIN. (POSTOP.)	PORTION OF VENTRICLE EXCISED
C 5	12.0	2.4	2.3	LAD*
C 6	15.0	1.0	0.5	LAD
C 7	23.2	4.8	1.3	LAD
C 8	15.4	3.9	1.2	LAD
C 9	9.3	0.7	0.7	LC†
C 11	12.3	1.3	1.9	LAD
C 12	15.0	2.0	1.0	LAD
C 13	17.0	1.5	1.1	LAD
C 14	15.0	3.2	1.8	LAD
C 17	13.1	3.0	1.3	LAD
C 18	18.9	2.9	1.1	LAD
C 19	12.5	1.6	1.2	LAD
C 21	18.2	3.4	0.7	LAD
C 22	19.5	2.3	1.9	LAD
C 29	22.7	6.1	6.4	LC
C 32	10	0.9	0.4	LC

*LAD = Area of heart supplied by branches of the left anterior descending coronary artery.

†LC = Area of heart supplied by branches of the left circumflex artery.

The data for the control group is shown in Table IV. In all 4 of the dogs which had the branch of the coronary artery ligated, there was a significant drop in the cardiac output. The 1 dog which had a return to normal cardiac output in 2 weeks had no evidence of infarction at autopsy 3 weeks after operation (CA 79). Dog B 12 had a return to preoperative cardiac output at 4 weeks, and at autopsy was found to have an infarction which was small and extended only about halfway through the thickness of the myocardium. Dogs CA 52 and CA 74 did not have a return of the cardiac output to preoperative levels at 4 weeks and 6 weeks postoperatively. At autopsy both were found to have healing infarcts involving the full thickness of the myocardium.

Of the group of 5 dogs which had sham operations, only 1 (B 7) had a significant fall in cardiac output immediately after operation. There was a return to preoperative output at 2 weeks.

TABLE IV. CARDIAC OUTPUTS IN LITERS PER MINUTE ON CONTROL DOGS

DOG NUMBER	WEIGHT (KG.)	INITIAL	IMMEDIATELY POSTOP.	2 WEEKS POSTOP.	4 WEEKS POSTOP.	6 WEEKS POSTOP.
			Coronary Artery Branch Tied			
CA 79	11.3	2.2	1.3	3.2		
CA 74	7.7	1.7	0.9	1.3	1.0	
B 12	9.1	2.1	1.2	1.3	2.1	
CA 52	18.6	6.0	3.6	3.2	4.0	4.2
			Sham Operation			
B 7	12.7	4.0	2.4	4.4		
CA 85	23.2	3.4	3.1	5.7		
B 5	10.9	3.1	2.9			
81	10.4	2.3	2.3			
36	11.8	1.4	1.2			

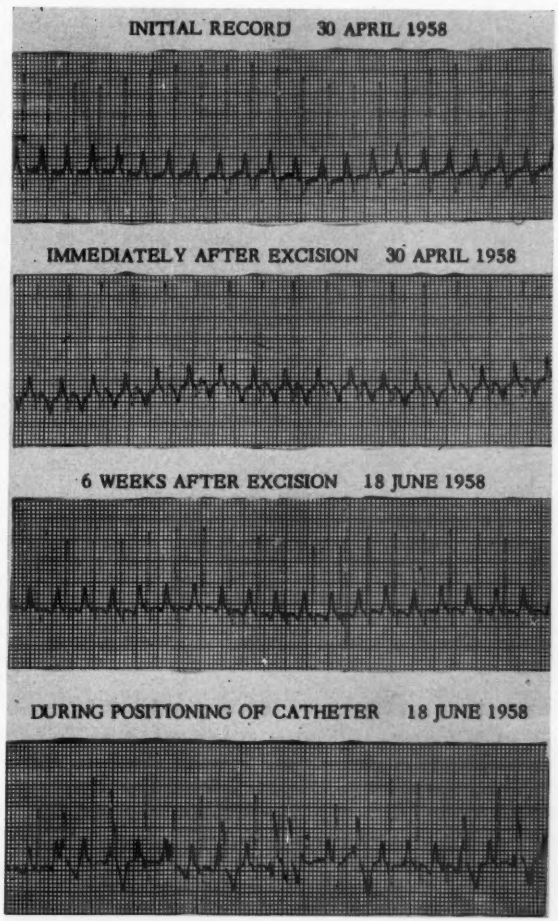
INITIAL RECORD 30 APRIL 1958
IMMEDIATELY AFTER EXCISION 30 APRIL 1958
6 WEEKS AFTER EXCISION 18 JUNE 1958
DURING POSITIONING OF CATHETER 18 JUNE 1958

Fig. 1.—Lead III of the electrocardiogram in Dog C 10 demonstrates the minimal charges associated with ligation of the branches of the left anterior descending coronary artery and excision of the cyanotic portion of the myocardium.

ELECTROCARDIOGRAPHIC CHANGES

The electrocardiographic changes were not striking in the group which had branches of the left anterior descending coronary artery ligated, and range from no significant change to T-wave inversion and slight S-T segment widening. Fig. 1 shows the changes in Lead III which occurred in Dog C 10. A period of a large number of ventricular complexes which occurred during positioning of the cardiac catheter in the right ventricle is also shown. This was found to occur in practically every one of 32 animals studied, but to a much less degree.

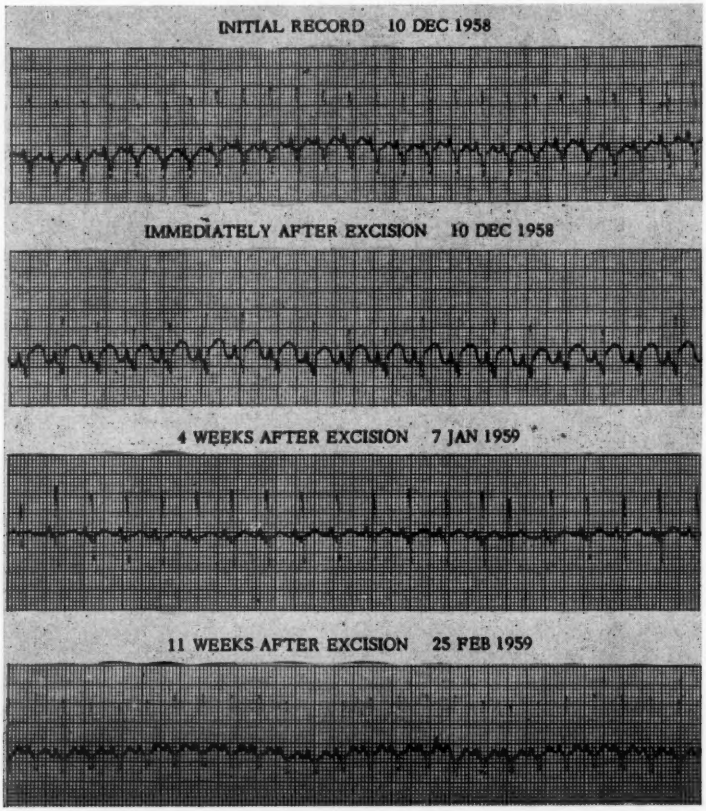
INITIAL RECORD 10 DEC 1958
IMMEDIATELY AFTER EXCISION 10 DEC 1958
4 WEEKS AFTER EXCISION 7 JAN 1959
11 WEEKS AFTER EXCISION 25 FEB 1959

Fig. 2.—Lead III of the electrocardiogram in Dog C 30 demonstrates the acute injury pattern after ligation of a branch of the left circumflex coronary artery and excision of the cyanotic area of myocardium. Note the recovery at 4 weeks.

In the group which had ventricular resection after a branch of the left circumflex artery was ligated, more striking changes were found. These changes were an acute injury pattern with S-T elevation and T-wave inversion as shown in Fig. 2.

In the control group with ligation of a branch of the anterior descending coronary artery, there were minor electrocardiographic changes similar to those

seen in the excision group. These changes had all reverted to normal by the second week after ligation.

In the control group with a sham operation, only 1 of the 5 showed electrocardiographic changes. This dog (CA 85) had 30-second occlusion of a large proximal branch of the left anterior descending coronary artery, and developed an acute injury pattern which had reverted to normal within 30 minutes.

In both the operative and control group, the electrocardiographic changes had returned to normal within 2 weeks.

VENTRICULAR FIBRILLATION

Ventricular fibrillation occurred six times. On the first two occasions, an electrical defibrillator was not available and both dogs died. Electrical defibrillation was successful in the other 4, but 1 dog did not recover satisfactory heart efficiency and died within an hour. Fibrillation occurred once prior to ligation and the others within 30 minutes after coronary artery ligation. Ventricular fibrillation did not occur in the control group.

BLOOD PRESSURE

There was no precipitous drop in blood pressure that correlated with ligation of the coronary artery. Twenty-seven dogs had the blood pressure recorded before, during, and after the operative procedure. In 18 of these, there was a transient fall in blood pressure associated with manipulation of the heart. This averaged about 65 mm. Hg fall in the systolic blood pressure. In 9, there was a transient average rise of blood pressure of 9 mm. Hg. By the end of the procedure there was an average fall in the systolic blood pressure of 55 mm. Hg in 24 of the dogs. Three had an average rise of 10 mm. Hg in the systolic blood pressure at the end of the procedure, and 2 of these 3 also did not have a fall in the cardiac output. Conversely, of the 4 dogs which did not have a drop in the cardiac output at the end of the procedure, 2 had a rise in the systolic blood pressure, and the other 2 did not have the blood pressure measured. In those dogs which had subsequent cardiac outputs done, the lowered systolic blood pressure had returned to normal preoperative levels in all but 3 (C 23, C 27, and C 28).

In the control group with ligation of a branch of the left anterior descending coronary artery, there was no fall in the blood pressure associated with the actual vessel ligation. There was an average fall in the systolic blood pressure in these 4 dogs of 40 mm. Hg from beginning to end of the operation. Two weeks after operation there was an average rise in the systolic blood pressure of 15 mm. Hg above the preoperative level.

In the control group with a sham operation, there was an average fall in systolic pressure of 20 mm. Hg below the preoperative levels.

DISCUSSION

The high incidence of disruption of the cardiac wounds found at autopsy was due to strangulation of the tissues by the mattress suture technique. This

finding was also demonstrated by Carter and MacMillan.[3] The lower rate of wound disruption in those dogs which had areas excised that were supplied by branches of the left circumflex coronary artery was probably due to the partial covering effect of the posterior papillary muscle over the myocardial wound. A two- and three-layer closure of continuous sutures with the aid of extracorporeal circulation gives a much more satisfactory approximation of the wound edges. None of the 3 dogs, however, closed in this manner survived beyond the first postoperative day due to brain damage, and no long-time wound studies have been done. Our experience with one human case, using a mattress type of suture technique for a large ventricular aneurysm, resulted in a false aneurysm developing at the suture line which required re-operation in 4 months.

Congestive heart failure was not a problem in these dogs which was probably because of the small area of myocardium involved. There was 1 dog in which decompensation did develop and this was thought to be due to mitral insufficiency from catching and fixing the chordae tendineae of the mitral valve in the suture line.

The cardiac output was shown to fall in the control group from ligation of a coronary artery, if an area of cyanosis and absence of contraction was produced. It was also shown in this group that if infarction was not produced (CA 79) or if the area of infarction was small and did not involve the full thickness of the myocardium (B 12), the return to preoperative output was rather rapid, within 2 to 4 weeks. Normal function did not return within 4 to 6 weeks in 2 dogs which had an infarction involving the full thickness of the myocardium. These findings in the control group substantiate the findings in the operative group (see Table II) which was followed for many months. At autopsy the myocardial scar was similar in size and appearance to the scar produced by infarction from ligating a coronary artery. The control group of sham operations demonstrated that thoracotomy and manipulation of the heart affect the cardiac output very little.

The electrocardiographic changes which in some cases were very striking did not persist for long. All animals were restudied within 2 to 6 weeks after operation. In every dog which survived for follow-up study, the electrocardiogram had returned to normal.

No correlation could be found between the blood pressure changes and cardiac output which was not surprising, in view of the mechanisms of blood pressure control.

SUMMARY AND CONCLUSIONS

Thirty-two dogs had a branch of the coronary artery ligated which produced a small area of cyanosis over an area of the left ventricle. The area of cyanosis was excised, and the animals studied at intervals before and after operation for changes in the clinical course, cardiac output, blood pressure, electrocardiogram, and morphologic changes in the heart. One control group of 4 dogs with various branches of the coronary arteries ligated was studied in a similar manner as was another control group of 5 dogs with a sham operation.

Ligation alone or ligation with excision of the cyanotic myocardium produced similar changes in the cardiac output, electrocardiogram, and morphology of the myocardium. Thoracotomy and manipulation of the heart produced little or no changes in the areas investigated in a control group of animals.

There appears to be no advantage to excising an area of small acute myocardial infarction in which the resulting scar will be as large as the scar from the healing infarct. The mattress suture technique used in these experiments is unsatisfactory due to strangulation of the myocardium and frequent rupture of the suture line.

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EXPERIMENTAL TEFLON REPLACEMENT OF THE SUPERIOR VENA CAVA AND ATRIOCAVAL JUNCTION

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INTRODUCTION

CONTINUING STUDY of suitable replacements for the superior vena cava and its atrial junction is advisable because of the serious consequences of occlusion[19] of these structures by neoplasm,[1] inflammatory conditions, or trauma. If the block is short, excision and direct anastomosis of the superior vena cava to the right atrium has been shown to be feasible by Gerbode and colleagues,[7, 8] and more recently by Riberi and Moore.[23] For the management of longer blocks, Sauvage and Wesolowski,[24] Scannell and Shaw,[25] and Schauble and associates[26] have reported satisfactory results with the use of venous grafts, while other authors[3] did not find vein grafts satisfactory. In 1954, Holman and Steinberg[18] reported successful relief of human superior vena caval occlusion using an homologous arterial graft, while Ohara and Sakai,[22] and MacLean and associates[21] concluded that such arterial segments were unsatisfactory in dogs. Many different fabrics of plastic material have been employed to replace veins. Nylon, Dacron, Orlon, and Ivalon fabrics or polyethylene tubes are not satisfactory materials for use as experimental venous prostheses according to reports by Egdahl, Hume, and Schlang,[5, 6] Deterling and Bhonslay,[3, 4] and MacLean and colleagues.[21]

From these reports it would appear that the successful grafting of great veins is considerably more capricious than is the replacement of arterial segments. The relatively slow venous blood flow and the ease of mechanical distortion of suture lines in the low pressure venous system must contribute to the poor results obtained when grafts or prosthetic materials are placed to bridge venous defects.

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Recent reports on the surgical characteristics of the new tetrafluorethylene fabric, Teflon, have suggested that this material might prove superior to other prostheses applied to the venous system. Teflon has performed well when used for arterial replacement[9-11, 13-17] and it has been apparent from the studies of Girvin and his co-workers,[9] Harrison,[13, 14] and LeVeen and Barberio[20] that the substance causes minimal tissue reaction. Consequently, we have undertaken an experimental study of superior vena caval replacement with this type of fabric tube.

METHODS

Stock mongrel dogs, varying in weight from 10 to 15 Kg., were anesthetized with Pentothal administered intravenously in concentrations of 25 mg. per kilogram of body weight. A right thoracotomy was carried out. The superior vena cava and upper portion of the right atrium were exposed by incision of the mediastinal pleura and pericardium. Care was taken to avoid injury to the adventitial planes of the vena cava. The azygos vein was divided between ligatures. Potts ductus clamps were applied to the vena cava or atrium, suitable segments of the vessel excised, and prosthetic replacement carried out. The prosthetic device inserted was the crimped, woven, tetrafluorethylene fabric, 12 mm. in diameter.* The grafts were not preclotted. The field was moistened with saline solution but anticoagulants were not used.

In one group of animals, segments of the superior vena cava, varying in length from 2 to 4 cm., were excised and were replaced by the fabric. The anastomoses were carried out by continuous glover's suture of atraumatic 4-0 silk.

In the second group of animals, similar lengths of the superior vena cava were excised including the atriocaval junction; the atrial defect was closed with sutures, and the Teflon prosthesis connected between the distal superior vena cava and a linear defect placed in the side of the right atrium immediately adjacent to the atriocaval junction.

Postoperatively the animals were given injections of penicillin and streptomycin for a period of several days and were then placed on full activity in an animal run.

RESULTS

We have placed 30 grafts in defects in the superior vena cava. Of these animals, 11 died between 1 and 60 days after operation, 5 died of postoperative shock within 24 hours, 3 died of empyema, and 3 died of hydrothorax secondary to thrombosis of the graft and progressive deterioration. The development of graft thrombosis was demonstrated by a loss of vitality, appetite, and hair, and ventilatory disturbance. In the 8 animals that died of shock and empyema, one graft was partially obstructed by thrombus and seven were found to be completely patent.

*Edwards-type Teflon arterial graft, manufactured by the United States Catheter and Instrument Co., Glens Falls, New York; distributed by C. R. Bard, Inc., Summit, N. J.

Of 19 long-term survivors in apparent normal health, ten grafts have been completely patent, six partially narrowed, and three thrombosed completely. Of the ten patent grafts, three showed slight narrowing of the anastomosis without consequence to the blood flow through the graft. Of the six grafts that became partially occluded, four have shown a small thrombosis and two a

Fig. 1.

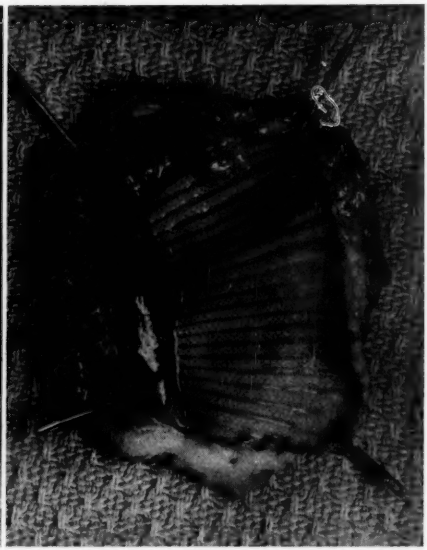

Fig. 2.

Fig. 1.—Teflon prosthesis in situ in the superior vena cava 9 months after operation. Absence of significant tissue reaction about the graft is apparent. Prosthesis is stiff enough to hold the lumen of the vena cava open along each suture line.

Fig. 2.—Interior of the same prosthesis. Suture line is not contracted at either end of the prosthesis.

TABLE I. SUPERIOR VENA CAVAL GRAFTS (TOTAL FOLLOW-UP)

TIME AFTER OPERATION	NUMBER	PATENCY	PARTIAL OBSTRUCTION, NARROWING, OR THROMBOSIS	TOTAL OBSTRUCTION BY THROMBOSIS
24 hr.	5	5	0	0
5 da.	1	1	0	0
1 wk.	2	1	1	0
2 wk.	3	2	0	1
3 wk.	1	1	0	0
1 mo.	1	0	1	0
2 mo.	3	1	0	2
3 mo.	1	0	1	0
4 mo.	1	0	1	0
5 mo.	2	1	0	1
6 mo.	2	1	1	0
7 mo.	2	1	0	1
8 mo.	2	1	1	0
9 mo.	2	1	0	1
10 mo.	2	1	1	0
Totals	30	17	7	6

marked narrowing as a result of the contracture of the anastomosis. The three completely obstructed grafts have revealed thrombosis involving the entire prosthesis (Table I).

A graft was placed at the atriocaval junction in 7 animals. Four animals died between 1 and 22 days after operation, 2 died of postoperative shock, and 2 of hydrothorax resulting from total prosthesis thrombosis. Of the 3 survivors, one graft was patent after 1 month, and two grafts were narrowed by contracture of the atrial suture line at 3 and 6 months, respectively, after operation. In 2 of the nonsurvivors, the grafts were completely obstructed at 7 and 22 days after operation (Table II).

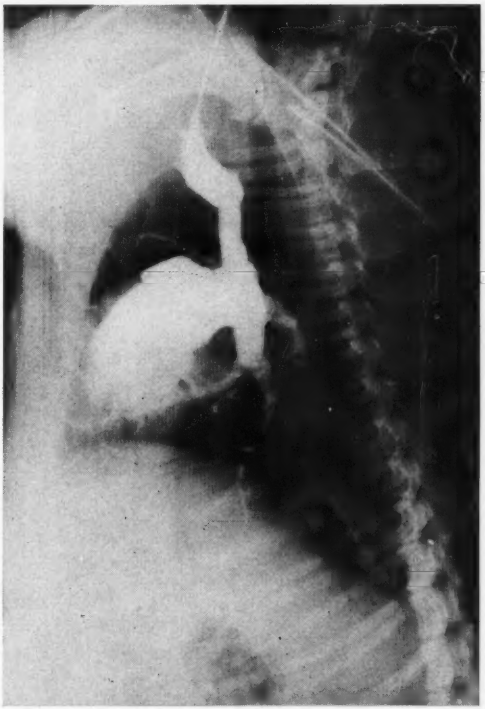

Fig. 3.—Venogram illustrating wide patency of a cavo-caval Teflon prosthesis at 10 months.

TABLE II. ATRIOCAVAL JUNCTION GRAFTS (TOTAL FOLLOW-UP)

TIME AFTER OPERATION	NUMBER	PATENCY	PARTIAL OBSTRUCTION	TOTAL OBSTRUCTION
24 hr.	2	2	0	0
1 wk.	1	0	0	1
3 wk.	1	0	0	1
1 mo.	1	1	0	0
3 mo.	1	0	1	0
6 mo.	1	0	1	0
Totals	7	3	2	2

Fig. 4.—Atriocaval prosthesis at 6 months. There is evidence of moderate contracture of the atrial suture line, but the graft is completely endothelized and patent. This degree of narrowing at the atrial suture line would be classified as "partial occlusion."

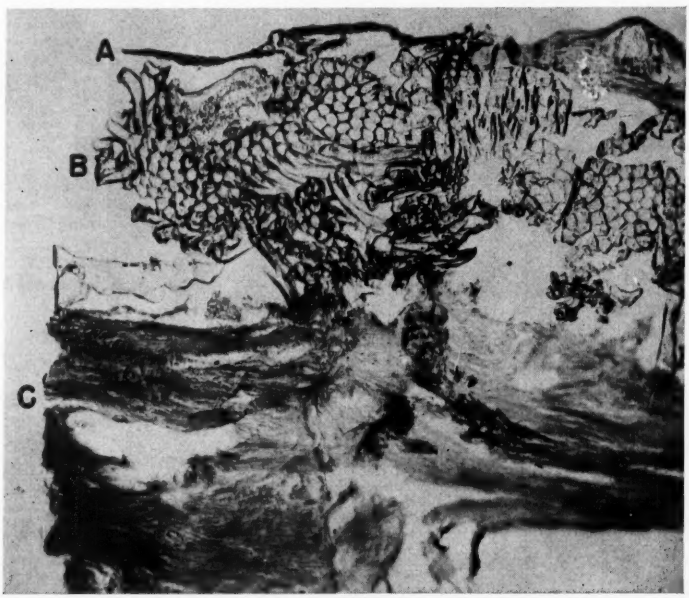

Fig. 5.—Teflon prosthesis at 9 months (×100; reduced 1/10). *A*, Endothelial surface; *B*, Teflon; *C*, perivascular fibrous tissue. Note the absence of tissue reaction about the plastic fabric.

DISCUSSION

Teflon fabric was easy to suture and the edge of the vessel and graft was well everted by a single, continuous glover's suture line. The corrugated nature of the tube would appear to present advantages in maintaining patency after venous anastomosis since such a fabrication has a stentlike action on luminal shape and suture lines are well separated. The importance of holding an atriocaval anastomosis open has been emphasized by Benvenuto and Lewis.[2] A similar stenting action may account for the success of an Ivalon-Lucite prosthesis placed by MacLean and colleagues[21] in the inferior vena cava.

It has been shown by Harrison and co-workers[12, 17] and LeVeen and Barberio[20] that Teflon causes minimal tissue reaction and this has been confirmed by our own study. There is little fibrotic reaction along the exterior walls of the prosthesis and complete absence of collapse of the prosthesis secondary to external compression.

Ivalon, Dacron, nylon, and Orlon used as venous prostheses have been widely studied by Deterling and Bhonslay,[3] Egdahl,[6] and MacLean and associates,[21] Ohara and Sakai,[22] Sauvage and Wesolowski,[24] and Schauble and coworkers[26] and have been found generally unsatisfactory because of a tendency to become obstructed by early thrombosis. In comparison with these studies, we have found Teflon to have a higher patency rate. There has been no time limit at which all grafts have become occluded. Obstruction by thrombosis has occurred between 1 week and 10 months.

When a graft has thrombosed gradually, development of collateral circulation has usually been sufficient to allow adequate superior caval return to the heart. When total graft obstruction was present, it was always secondary to thrombosis originating at a suture line. In some instances, narrowing has been found to occlude the graft partially, usually at only one end of the prosthesis. In no instance has associated collapse of the prosthesis been noted and, when thrombosed, it has remained free of contracture and has retained its original shape.

The general appearance and behavior of the animals usually indicated that a graft was becoming obstructed. Edema of the head and upper extremities has not occurred, but there has been a loss of vitality and weight. The absence of edema and slow progression of other signs have been considered secondary to the extensive collateral circulation developed.

In conjunction with the finding of a relatively low incidence of occlusions (all arising at the suture line), it must be remembered that the human being does not possess as active a coagulation mechanism as the dog so that minor irregularities in the suture lines would be more likely to cause thrombosis in the dog than in the human being. These facts have led us to believe that the larger Teflon prostheses required for human superior caval replacement would be even more likely to succeed. We have placed two such prostheses in human beings and have been favorably impressed by their initial characteristics. Details of the operative procedures and long-term follow-up will be presented in a future publication.

SUMMARY

The superior vena cava and atriocaval junction have been replaced in a series of dogs by Edwards-type, Teflon arterial graft fabric. After a follow-up period of 10 months of thirty grafts in the superior vena cava, seventeen have been found patent, seven partially obstructed, and six totally obstructed. During the same period, three of seven atriocaval grafts have been found to remain patent, one has been partially obstructed, and three totally obstructed.

We are indebted to Mr. Norman Jeckel of the United States Catheter and Instrument Co., Glens Falls, New York, and Mr. Alfred B. Beers of the C. R. Bard Inc., for the Teflon prostheses used in this study.

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A SIMPLIFIED TECHNIQUE FOR CLOSURE OF INTERVENTRICULAR SEPTAL DEFECTS

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THE TECHNICAL difficulties of precisely placing sutures in interventricular septal defects are well known to cardiac surgeons. A right ventriculotomy which does not traverse major coronary vessels often does not provide ideal exposure of the ventricular septum in the defect area, and the septal leaflet of the tricuspid valve often obscures the lower edge of the defect. Under these circumstances it is frequently awkward or impossible to place an ordinary suture needle in the ideal location and proper direction through the tissue. A large curved needle is difficult to manipulate in the limited exposure and a smaller needle may be impossible to grasp when placed through the septal edge.

An ordinary needle holder can be manipulated only by rotation on its long axis, particularly when it is introduced into a confined space. Motion of the needle it grasps is thus necessarily limited to the plane at right angles, regardless of how it is mounted or the curvature in the jaws (Fig. 1). Directing the needle in any other plane is reflected by motion of the instrument handle as a long lever. This motion is manifestly awkward or impossible inside the ventricle. Nevertheless, the desired needle direction is often in a plane parallel to, or at acute angles to, the axis of the needle holder.

To solve this difficulty, a simple curved needle hook is used as described in the accompanying diagrams (Fig. 2). It is easily handled and directed; its total size is small and does not obscure the field. Its piercing arm is sufficiently long to be easily seen, and it has no tail to snare or pierce adjacent tissues. Its only drawback is the necessity of passing double thicknesses of suture material adjacent to the needle through the septum; however, the size of this puncture hole is not significant and is doubtless smaller than some holes produced by the tearing action of misdirected needles. Furthermore, the direction

Fig. 2.—Technical steps in placing a mattress suture through the septal edge.

1, The needle is mounted with the arm of suture through the inside of the needle grasped with the handle; the short free end extends through the outside of the hook as it penetrates the tissue.

2, The outside loop is snared to draw the *a* end through.

3, With the *a* end secured, the needle tip is withdrawn and the *b* end is released from the operator's grip.

4, The other side of the mattress suture is begun with the second needle pierce.

5, The outside loop is again snared to pull through the *b* end.

6, The hook needle is withdrawn, leaving the mattress suture in place.

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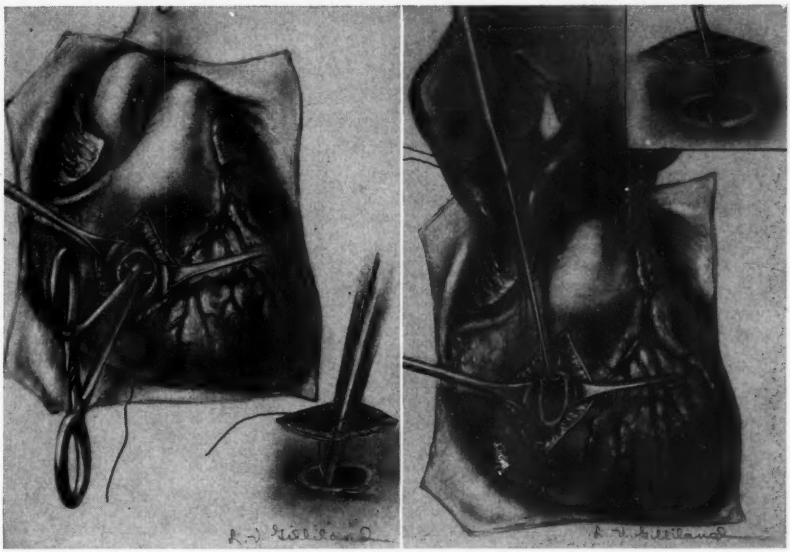

A. *B.*

Fig. 1.—A curved needle mounted on a needle holder *(A)* cannot be directed through the septal tissue without obliquity. The hook needle *(B)*, with the point parallel to the shaft, can be drawn with a simple upward motion.

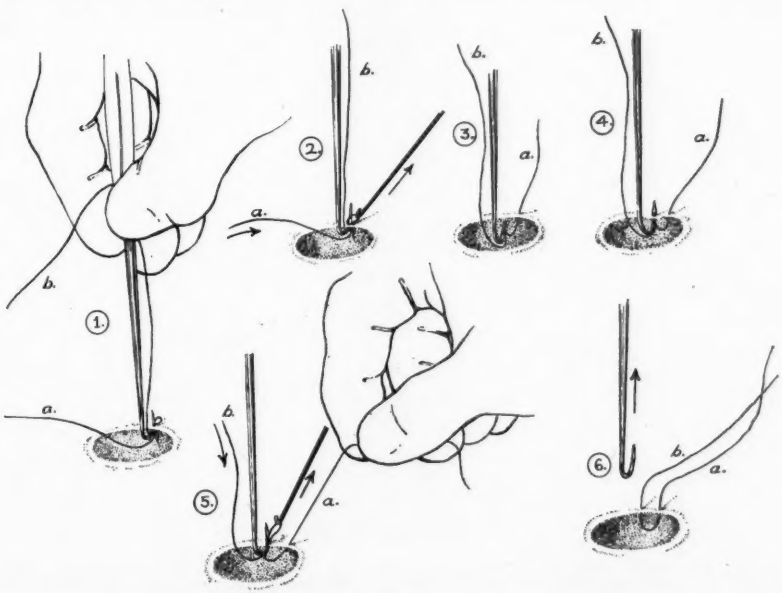

Fig. 2.—*For legend see opposite page.*

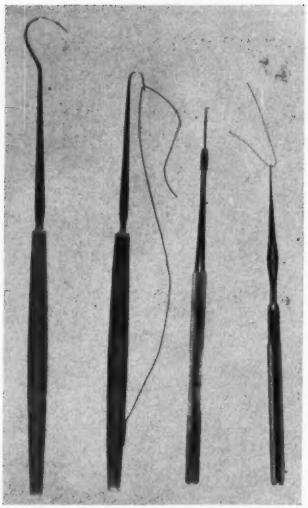

Fig. 3.

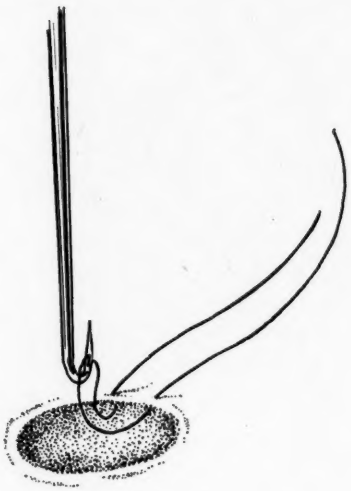

Fig. 4.

Fig. 3.—Instruments used, left to right. Tonsil needle from which hooks were adapted. Hook needle used in this technique. Dura hook for snaring suture loop of needle eye. Crotchet needle.

Fig. 4.—Result if wrong loop is snared from the needle holder in the second stage. Suture will have to be withdrawn if this occurs.

Fig. 5.—Special curved hollow needle with spool of suture material delivered through tip. The piercing arm of this needle is a No. 22 hypodermic size. In effect, the *b* arm of the suture loop in Fig. 2 is in the shaft of the instrument, rather than floating loose.

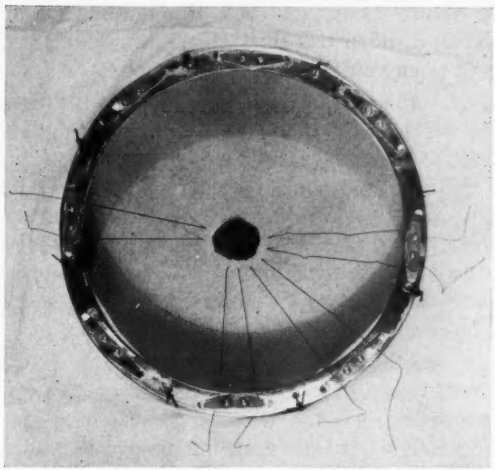

Fig. 6.—The Figure shows the suture ring with 8 clips showing sutures in place, draped over a special sheet which covers the rest of the operative field.

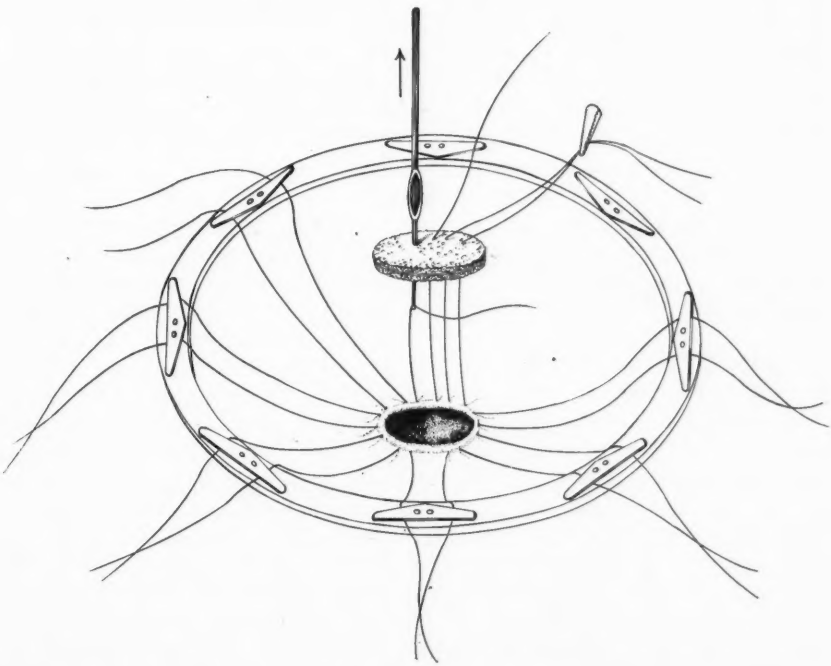

Fig. 7.—The use of the crochet hook to travel suture ends through the plastic sponge patch is demonstrated. The crochet hook penetrates the patch in the desired position and the proper suture end is looped on to it and it is withdrawn.

of tension on the suture tends to be in a straight line through the septum; a curved needle travels through this thick tissue in a circular course which must be distorted or torn when straight tension is applied.

This method of suturing can be accomplished as illustrated with a simple tonsil hook needle which has been rebent into a more suitable curve (Fig. 3). Practice is required to snare the correct side of the loop with a sharp pin hook so as not to tear the delicate septal tissue and not to have the loop left through the needle eye after both ends are through the tissue (Fig. 4). A new instrument has been developed to facilitate this maneuver and to reduce the size of the needle puncture hole. It consists of a hollow shaft and needle tip (No. 22 hypodermic needle) which carries the suture and delivers a single end of suture from a spool on the handle (Fig. 5).

The technique is rapid for several reasons: (1) the hook is easy to handle and simple to direct into the desired position; (2) both arms of the mattress suture are introduced with a single mounting in the needle, thus obviating the withdrawal of the needle holder and grasping a separate needle; (3) the absence of multiple needles around the incision and the use of a suture ring (Fig. 6) reduces the tangle in the operative field; and (4) the crochet hook facilitates bringing the sutures through the patch material with a simple straight down and up motion (Fig. 7) obviating the multiple maneuvers of mounting, grasping, and cutting 12 to 16 curved needles.

Experience with this technique in the closure of ventricular septal defects, when patches have been used, has significantly reduced the operating time during cardiotomy and largely obviated the necessity of elective cardioplegia.

SUMMARY

A simplified timesaving technique for introduction of sutures in confined areas is described. Its application for placing of mattress sutures for closure of interventricular septal defects with patches has significantly reduced operating time.

AN EFFECTIVE BLOOD HEAT EXCHANGER FOR DEEP HYPOTHERMIA IN ASSOCIATION WITH EXTRACORPOREAL CIRCULATION BUT EXCLUDING THE OXYGENATOR

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EXTRACORPOREAL CIRCULATION with deep hypothermia has made it possible to perform prolonged intracardiac operations in a bloodless field without the use of an oxygenator as shown by Drew. Deep hypothermia is therefore an alternative to the pump-oxygenator. The aim of this paper is to describe a heat exchanger which has proved effective in experiments as well as in clinical cases for the induction of deep hypothermia.

METHOD

Thirty-nine perfusions with a disc oxygenator were first performed to provide a basis for comparison. Then the method of deep hypothermia with extracorporeal circulation was tried on dogs, utilizing the same pumps, tubings, connectors, reservoirs, and filter. The disc oxygenator was replaced by a heat exchanger. In the animal experiments, a subcostal incision was made under the fourth rib on the right side. Heparin, 2 mg. per kilogram of body weight, was injected directly into the right atrium. One cannula (Bardic catheter) was introduced through the interatrial groove into the left atrium and another into the right atrium through its appendix. These two cannulas were connected with reservoirs. A metal cannula was introduced into the femoral artery in the usual fashion (Fig. 1).

The perfusion was begun by draining blood from the left atrium at a rate of 100 to 250 ml. per minute into a reservoir. The blood was then pumped through the heat exchanger and a filter into the femoral artery. After 10 to 20 minutes, the esophageal and rectal temperature reached 18° to 22° C. and the heart went into ventricular fibrillation. The left-sided perfusion was then stopped while a cannula was introduced into the main pulmonary artery through a stab wound in the right ventricular wall. Blood from the right atrium was drained into a reservoir and pumped through this tube into the pulmonary artery, oxygenated in the lungs and returned to the left atrium and to the left-sided perfusion. In other words, one pump acted for the left, one for the right ventricle. The blood was cooled or warmed in the left perfusion circuit and oxygenated by the lungs in the right circuit (Fig. 1).

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Once fibrillation occurred, the left perfusion was momentarily stopped, then the left and right perfusions were simultaneously begun at an approximate rate of 50 ml. per kilogram of body weight per minute. Within 15 to 20 minutes the esophageal temperature was brought below 10° C. Oxygen consumption is low at this low temperature and the relatively high flow loads the tissues with oxygen. Then the perfusion was stopped, the superior and inferior venae cavae as well as the aorta and the pulmonary artery were occluded. This

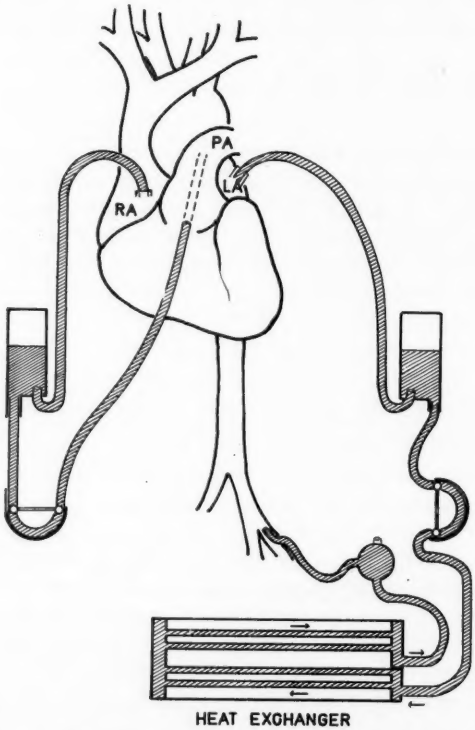

Fig. 1.—Diagram of the cannulation of left atrium, right atrium, femoral artery, and pulmonary artery for deep hypothermia. The left circuit includes the heat exchanger and the right circuit provides oxygenation in the patient's own lungs (according to Drew).

placed the heart in hypothermic arrest, and a right ventriculotomy was performed. The right ventricle was left open for 30 minutes, then filled with glucose and the left and right perfusions started again at an approximate rate of 50 ml. per kilogram per minute. At a temperature of about 30° C. the heart spontaneously resumed its regular rhythm or was electrically shocked. The right perfusion was stopped and the right atrium and the pulmonary artery were decannulated. The left perfusion was continued for rewarming until a rectal temperature of 34° C. and an esophageal temperature of about 38° C. were reached. After decannulation, 3 mg. of protamine were administered and the wound was closed.

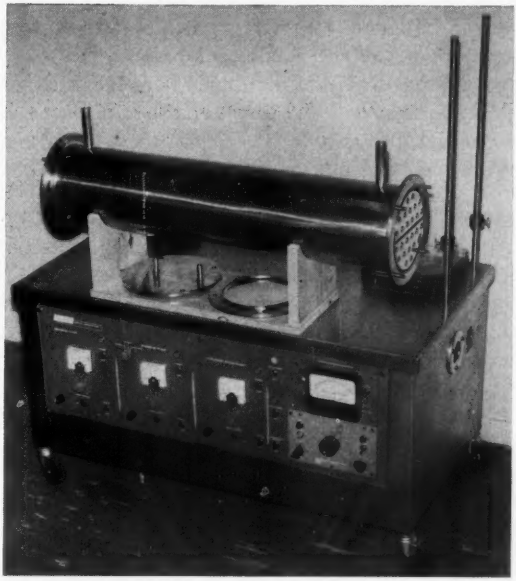

Fig. 2.—The heat exchanger mounted on a Mark machine with two De Bakey roller pumps. The blood enters the tube in the lower part of the cylinder and comes back through the tubes in the upper part of the cylinder. The water for cooling and warming enters the upper connections.

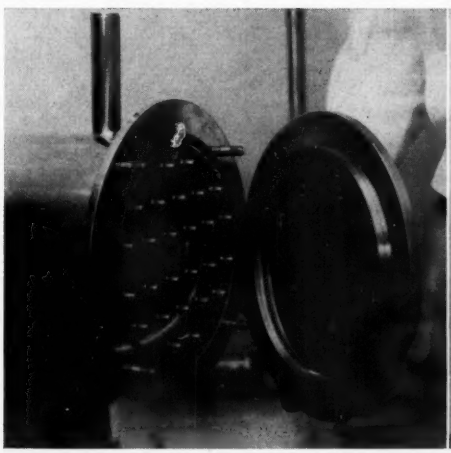

Fig. 3.

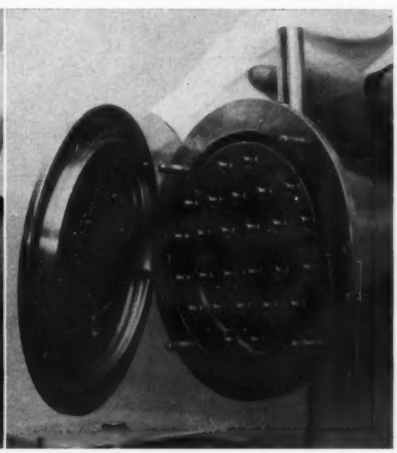

Fig. 4.

Fig. 3.—Demonstrating one end of the heat exchanger with the rod in place.

Fig. 4.—Demonstrating the other end of the heat exchanger where the blood enters in the lower portion and leaves in the upper portion of the heat exchanger.

The heat exchanger was built of stainless steel tubes mounted in a stainless steel cylinder (Figs. 2, 3 and 4). The tubes are 80 cm. long and have an internal diameter of 1 cm. thereby making mechanical cleaning easy. Into each tube a stainless steel rod of 7 mm. external diameter with rounded edges is introduced. By these measures (1) the perfusion pressure is not increased at a flow up to 3,000 ml. per minute, (2) 900 ml. less blood is needed, and (3) the cooling or warming efficiency on the thinner layer of blood is increased

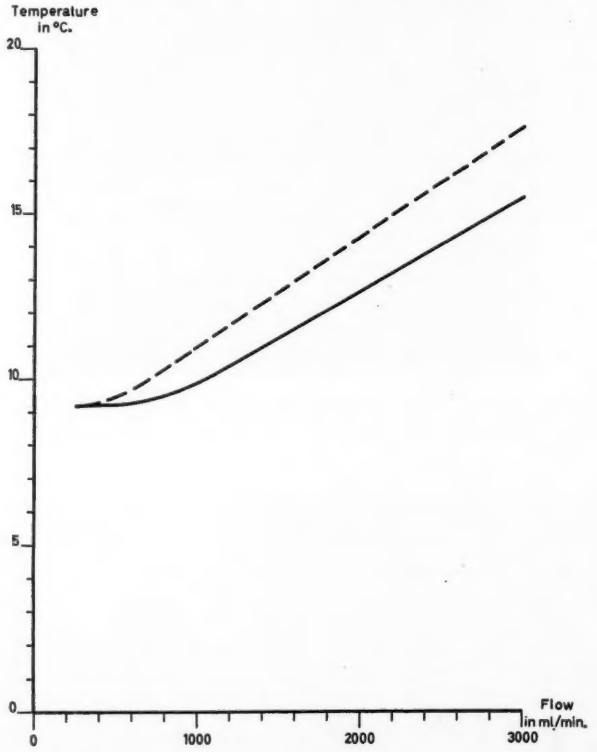

Fig. 5.—The cooling efficiency of the heat exchanger with the rods (*lower curve*) and without the rods (*upper curve*), demonstrating that at a very low flow the blood going through the heat exchanger once will have about the same temperature as the cooling fluid which during this experiment was 8° C. flowing through the heat exchanger at a rate 24 liters per minute. With a higher rate of blood flowing through the heat exchanger, the cooling efficiency was better if the rods inside the tubes were used (*lower curve*). At a flow rate of blood of 3,000 ml. per minute, the blood leaving the heat exchanger was 2° C. colder when the internal rods were used.

(Fig. 5). Through the cylinder outside the tubes, warm or cold water is circulated and the temperature thermostatically controlled by a Therm-O-Rite apparatus. For cooling water at a temperature of +2° C. and for warming water at a temperature of 41° C. at a flow of 6 L. per minute was used. A higher flow rate up to 25 liters is advised for adults. The blood leaving the heat exchanger should have a temperature of from 5° to 10° C. during the cooling and between 38° and 39.5° C. during rewarming.

RESULTS

First Step of Cooling.—From experiences thus far gained, it is considered that the first step of cooling should start with a rather slow perfusion rate of about 100 c.c. per minute in small patients and up to 1,000 ml. per minute in heavier patients. In this way ventricular fibrillation will occur at an esophageal temperature between 16.5° and 25.8° C., with a temperature approximately similar in the rectum.

We have investigated the oxygen tension in the blood leaving the heat exchanger at the slowest flow rate used, i.e., 100 ml. per minute, and found that after 6 minutes of perfusion an oxygen tension of 86 mm. Hg is reached. At such a slow perfusion rate, full saturation is reached in the blood which leaves the heat exchanger long before ventricular fibrillation occurs. Data for oxygen tension, checked every minute, of blood leaving the heat exchanger are given in Fig. 6. Data of rate of cooling and the occurrence of ventricular fibrillation at different flow rates and different temperatures are summarized in Table I.

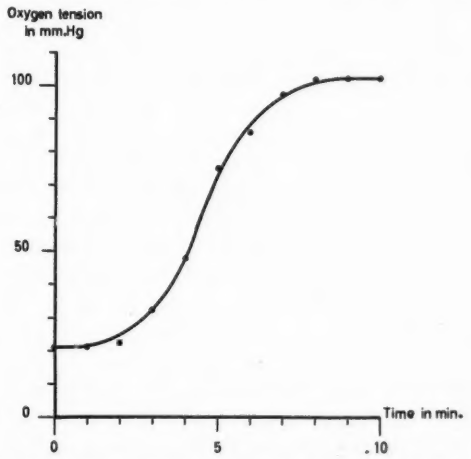

Fig. 6.—Curve showing the oxygen tension in the blood leaving the heat exchanger at a flow rate of 100 ml. per minute. Determinations were made every minute.

The Second Step of Cooling.—Once the ventricular fibrillation has started the left-sided perfusion is immediately stopped. Otherwise, there will be built up a high venous pressure during the time blood is pumped into the femoral artery but not being pumped away by the right heart.

Through a stab wound in the right ventricular wall, a Bardic catheter is put through into the pulmonary artery. It is important that the tip of the catheter be placed peripherally to the pulmonary valves. There is danger of leakage into the right ventricle in patients with high pulmonary resistance and, therefore, need for having an occlusion tape around the tip of the catheter. In cases of tight pulmonary valves in which it is difficut to introduce a Bardic catheter, a metal cannula similar to the one used in the femoral artery has been inserted. Once the catheter is in place, perfusion is started simultaneously

TABLE I. FIRST STEP OF COOLING*

	WEIGHT (KG.)	RATE OF PERFUSION (ML./MIN.)	TIME (MIN.)	TEMPERATURE (°C.) ESOPHAGUS	RECTUM	IN BLOOD LEAVING THE HEAT EXCHANGER	
Dog number							
40	30	1,500	10	31.6		+10	
41	20	2,000	3	25		+10	
42	24	1,400	3	37		9-7	
43	19	500	5	23.4	28.2	9	10
44	25.5	500	12	29.5	31.2	14	11.4
45	31	500	15	31.8			
Patient number							
2	13.6	100	16	17.8	17.5	4.5	4.5
6	15.6	100-250	22	18.9	18.7	4.5	2.5
7	26.5	250	11	17.0	23.8	11	9
4	28.3	100	10	20.2	22.3	3	5
5	51.8	100-250	24	19.6	21.0	2.5	5.5
1	65	250	18	19.0	17.3	4.5	9.7
3	73.7	250	18	25.8	23.8	3.5	7.5
8	50.0	500	9	30.0	24.0	4.5	10
9	19.1	100	27	16.5	14.4	3.0	4.5
10	15.4	100	16	16.3	24.5	3.5	4.0

*Blood drained from left atrium and pumped through the heat exchanger into the femoral artery until ventricular fibrillation occurs.

on the left and right sides. The left pump is increased until a rate of around 50 ml. per kilogram of body weight is reached, which flow rate is thought to be the ideal one since very little pressure gradient over the femoral cannula is obtained. The right pump is kept at about the same speed as the left one but regulated according to the level in the reservoir draining the left atrium. Once the blood in the left reservoir is low, the right pump speed is increased, which immediately will increase the level of blood in the left reservoir. The blood thus pumped through the lungs immediately drains down into the left reservoir and is pumped through the heat exchanger back into the femoral artery.

All dog experiments and clinical experiences with perfusion rates of the second step of cooling are summarized in Table II.

The second step of cooling should be done at a much higher speed than the first step. Probably a rate of 50 ml. per kilogram of body weight is ideal. This will not cause too high a pressure gradient over the arterial cannula and will lower the temperature as quickly as possible. There has been no difficulty in keeping the same flow rate on the right- or left-sided perfusion in all cases, except those in which the pulmonary cannula has slipped out or when there has been an abnormal venous return with an intact atrial septum or a very high pulmonary resistance.

The Temperature Change During Total Arrest in Deep Hypothermia.—As the room temperature is much higher than the temperature of the patient during deep hypothermia, it is important to know the increase in temperature during the total arrest. Furthermore it is important to know if that change or increase in temperature during the total arrest was more rapid if the cooling time was short as compared with a longer cooling time. These experiments are

TABLE II. SECOND STEP OF COOLING = TOTAL PERFUSION*

	WEIGHT (KG.)	RATE OF PERFUSION (ML./MIN.)	TIME FOR RIGHT + LEFT PERFUSION (MIN.)	TOTAL TIME FOR COOLING (MIN.)	TEMPERATURE AT TOTAL ARREST (°C.)		
					ESOPHAGUS	RECTUM	IN BLOOD LEAVING THE HEAT EXCHANGER
Dog Number							
40	30	2,000	60	70	16.7		
41	20	2,000	32	35	9.5	11.4	
42	24	1,400	58	60	9.0	16.0	7.0
43	19	1,500	18	23	9.5	14.8	10.0
44	25.5	2,000	42	54	10.0	17.1	11.4
45	31	1,500	51	66	10.4	15.2	
Patient Number							
2	13.6	700	14	30	5.8	15.4	5.0
6	15.6	800	7	29	10.0	18.4	6.0
7	26.5	1,300	5	16	10.0	21.8	7.5
4	28.3	1,000	26	36	7.8	20.0	5.3
5	51.8	2,200	10	34	10.0	21.0	8.5
1	65	2,290	12	30	14.7	16.0	11.7
3	73.7	2,000	27	45	7.5	19.0	11.7
8	50	2,500	24	33	10.0	19.2	6.0
9	19.1	800	8	35	10.0	12.4	3.0
10	15.4	750	5	21	10.0	21.0	3.0

*Left perfusion with cooling = first step plus drainage of blood from right atrium and pumping that blood back through the pulmonary artery (right perfusion with oxygenation of blood in the lungs). Left and right perfusion at the same rate was continued from ventricular fibrillation until complete arrest with cardiotomy.

shown in Table III, which shows that the shorter cooling time resulted in the highest temperature increase during the total arrest. The difference, however, is so small that it was considered to be without practical value. If too long a cooling time was used, the method would not be suitable for clinical use. Therefore in the clinical cases a trial was made to obtain a cooling time as short as possible.

TABLE III. THE TEMPERATURE CHANGE DURING TOTAL ARREST IN DEEP HYPOTHERMIA IN DOGS

DOG NUMBER	TOTAL TIME FOR COOLING (MIN.)	TOTAL ARREST (MIN.)	TEMPERATURE CHANGE (°C.)	
			ESOPHAGUS	RECTUM
43	23	30	+3.3	+0.4
41	35	30	+6.5	+4.6
44	54	30	+1.2	+1.9
42	60	30	+2.5	+1.5
45	66	40	+3.0	−1.2
40	70	30	+1.3	—

The temperature changes during total arrest in deep hypothermia in the patients are summarized in Table IV. From these data it can be concluded that there will always be a temperature increase both in the esophagus and in the rectum during the total arrest, increasing the metabolic needs of the patient. A period of total arrest longer than 45 minutes is not recommended for an adult and if it is evident after 40 minutes of surgery that more than 5 minutes' time is needed to complete the operation it is advised that a second short perfusion of cold blood for about 15 minutes be employed to again load the tissues with

oxygen. Furthermore, the very rapid cooling, as in Case 7, in which an esophageal temperature of 10° C. was reached in 16 minutes allowed a total arrest of 44 minutes with only 4.3° C. increase in temperature in the esophagus, followed by an excellent recovery.

TABLE IV. THE TEMPERATURE CHANGE DURING TOTAL ARREST IN DEEP HYPOTHERMIA IN PATIENTS

PATIENT NUMBER	TOTAL TIME FOR COOLING (MIN.)	TOTAL ARREST (MIN.)	TEMPERATURE CHANGE (°C.)	
			ESOPHAGUS	RECTUM
7	16	44	+4.3	+1.9
6	29	38	+5.0	+2.6
2	30	70	+9.6	+4.6
1	30	25	+0.9	+2.6
5	34	21	+3.8	+0.6
4	36	49	+6.7	+2.9
3	45	47	+2.2	+1.4
8	33	27	+1.6	+2.2
9	35	50	+3.4	+8.0
10	21	41	+7.3	+2.0

Rewarming.—The experiences from rewarming of patients are summarized in Table V. From that table it is found that the shortest total rewarming time was 27 minutes in a patient of only 15 kilograms. The longest rewarming time was 135 minutes and the next longest 91 minutes in a patient weighing 73.4 kilograms. A flow of approximately 50 c.c. per kilogram of body weight was used.

TABLE V. FIRST AND SECOND STEPS OF REWARMING*

CASE NUMBER	WEIGHT (KG.)	TOTAL WARMING TIME (MIN.)	FLOW (ML.)	FIRST STEP			REGULAR RHYTHM	SECOND STEP		
				TIME (MIN.)	TEMPERATURE			TIME (MIN.)	TEMPERATURE	
					ESOPH.	RECTUM			ESOPH.	RECTUM
6	15.6	33	800	12	31.8	27.5	Sp.†	21	38.6	33.0
7	26.5	34	1,300	9	33.0	27.2	Sp.	25	38.6	34.5
2	13.6	39.5	700	10	31.2	28.8	Sp.	29.5	38.0	34.2
5	51.8	72	2,000	16	34.4	24.6	Sp.	56	38.6	34.2
1	65	75	1,900	22	34.2	23.6	Shock	53	36.0	33.4
3	73.4	91	2,000	28	33.0	23.5	Shock	63	36.7	31.0
4	28.3	94	1,000	54	38.2	28.2	Shock	40	38.0	33.0
8	50.0	135	2,000	65	37.8	27.6	Shock	70	38.2	34.0
9	19.1	32	800	13	30.6	29.2	Sp.	19	38.4	33.4
10	15.4	27	750	11	34.5	28.4	Sp.	16	38.0	34.6

*First step of rewarming: left and right = total perfusion until regular heart rhythm occurs spontaneously or after an electric shock. Second step of rewarming with only left-sided perfusion.

†Spontaneously.

Regarding the first step of rewarming when both left- and right-sided perfusions were used simultaneously—this was continued until a regular heartbeat returned, which occurred spontaneously in 5 cases and probably would have occurred in Cases 1 and 3 if we had waited until higher rectal temperatures were reached. A regular heartbeat returned spontaneously at an esophageal temperature varying between 31.2 and 34.4° C., with a rectal temperature of 24.6 up to 28.8° C. In 2 cases, the hypothermic arrested heart resumed a regular rhythm at 20° C. without an intermediate ventricular fibrillation being observed.

It is evident therefore that one may have to wait until a rectal temperature of 28.8° C. has been reached before a regular heart rhythm will return spontaneously. The shortest rewarming time to obtain a regular heartbeat was 9 minutes in Case 7. In the 4 cases in which it was necessary to shock the heart to regain regular heart rhythm only one shock, 2.5 amperes and 0.16 second, was needed in 3 cases.

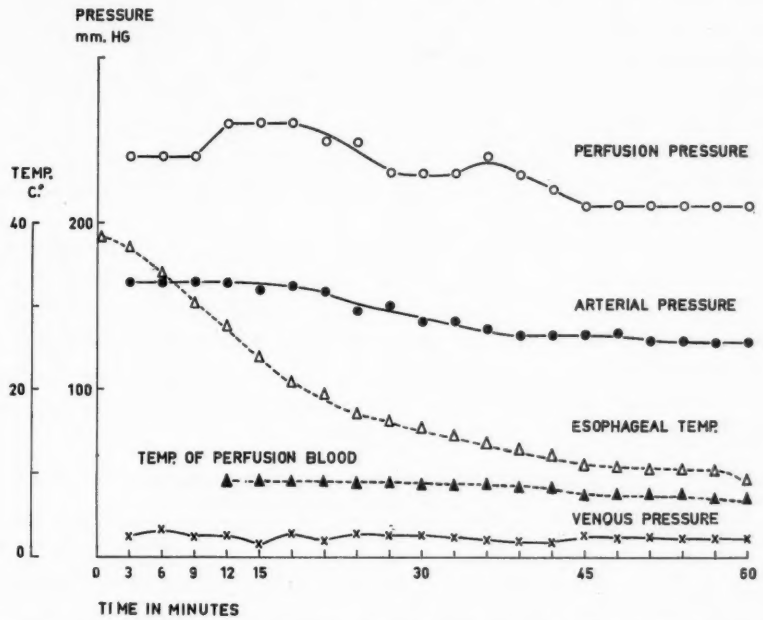

Fig. 7.—Diagram of a dog experiment under total perfusion in which it can be seen that the perfusion pressure rises during a cooling.

Once a regular heartbeat was restored, the right perfusion was immediately stopped, the cannula in the pulmonary artery and right atrium removed, and left-sided perfusion continued at the same rate. For the clinical cases we preferred to reach a rectal temperature above 34° C. before the left perfusion was stopped. Then the esophageal temperature was always above 38° C. and the patient regained consciousness rapidly after conclusion of the procedure.

In conclusion it can be said that the rewarming time has been dependent on the size of the patient and the flow of fluid through the heat exchanger. Our aim is to use a rewarming time as short as possible.

The Pressures in the Machine and in the Patient During the Perfusion (Fig 7).—If a total perfusion was carried out with a constant flow, it was found that during the cooling procedure only in the beginning there was an increased vascular resistance with increase in the pressure in the machine and an increase in the pressure gradient over the arterial cannula. This pressure gradient over

the cannula tended to be somewhat lower when the temperature was below 20° C. The pressure gradient over the arterial cannula was measured in the smallest patient, weighing 13.6 kilograms in whom a cannula of 3.5 mm. was utilized. Pressure in the machine at a flow of 700 ml. per minute varied between 170 and 155 mm. Hg when the patient's pressure was 85 to 75 mm. Hg. In the beginning of the rewarming period, the pressure was 135 mm. Hg but rose to 175 mm. Hg in the machine with a simultaneous rise in the patient of 60 to 90 mm. Hg. Corresponding measurements in the heaviest patient, weighing 73.7 kilograms, showed the highest pressure to be 300 mm. Hg in the machine at a flow of 2,500 ml. per minute with a simultaneous pressure of 70 mm. Hg in the patient. This was an occasional value; most values were 150 mm. Hg in the machine and 80 in the patient at a flow of 2,000 ml. per minute. During rewarming, the corresponding pressures were 240 mm. Hg in the machine and 80 mm. Hg in the patient.

Hemolysis.—The data of hemolysis are summarized in Table VI. It is immediately evident that in the animal experiments a plasma hemoglobin of 19 mg. per cent at the end of perfusion is extremely low, when compared with a plasma hemoglobin of 83 mg. per cent when a pump oxygenator was used. In patients a plasma hemoglobin level of only 14.4 mg. per cent was observed. These are the only data favoring the superiority of the method of employing a heat exchanger instead of a pump oxygenator.

TABLE VI. THE HEMOLYSIS OF THE BLOOD IN MG. % PLASMA HEMOGLOBIN AFTER DEEP HYPOTHERMIA WITH EXTRACORPOREAL CIRCULATION

	TOTAL TIME OF PERFUSION (MIN.)	HEMOLYSIS BEFORE PERFUSION		AFTER END OF PERFUSION	>2 HOURS AFTER PERFUSION
		ARTERY	MACHINE		
Dog number					
40	145	0	7	26	28
41	70	0	—	28	—
42	100	6	15	8	8
43	67	0	12	16	10
44	104	0	11	17	10
Mean values	97		11	19	14
Patient number					
1	105	3	5	5	—
2	69	12	38	18	0
3	136	3	15	10	0
4	130	2	8	18	20
5	106	6	—	17.5	—
6	62	0	—	28	0
7	50	0	2	28	0
8	168	4	—	11	5
9	67	0	—	6	5
10	48	0	6	2.5	0
Mean values	94	3	12	14.4	4

Thrombocytes.—The influence of the heparin dosage on the number of thrombocytes during deep hypothermia was studied in the following way. The heparin dosage was varied from 1.5 to 3 mg. per kilogram of body weight. At a dosage of 3 mg. per kilogram of body weight, the number of thrombocytes

fell from 191,000 to 90,000 at an esophageal temperature of 9.5° C. During rewarming the number of thrombocytes again increased to 224,000, still remaining at 224,000 at 2 hours after the end of perfusion. In the experiments in which 1.5 mg. heparin per kilogram of body weight was used, a fall from 161,000 to 63,000 thrombocytes at a temperature of 10.0° C. was observed. During rewarming the number of thrombocytes returned to 198,000 and 2 hours after the end of perfusion they numbered 171,000.

It can therefore be concluded that although there was a significant fall in the number of thrombocytes at low temperatures, a normal number of circulating thrombocytes was found during the rewarming process with a heparin dosage of 1.5 mg. per kilogram of body weight. A dosage of 2 mg. per kilogram of body weight was used in clinical cases, later this dose was increased to 5 mg. The values of the thrombocytes before, during, and after deep hypothermia in the clinical cases are summarized in Table VII. Although the number of thrombocytes may be as low as 34,000 at 7.8° C., the number has always been normal at the end of rewarming. After the end of the procedure, the heparin has been neutralized with protamine which has restored the bleeding and coagulation time to normal in all clinical cases in which there has been no problem with postoperative bleeding.

TABLE VII. THE NUMBER OF THROMBOCYTES IN THOUSANDS BEFORE, DURING, AND AFTER DEEP HYPOTHERMIA IN CLINICAL CASES

CASE NUMBER	BEFORE PERFUSION	AT THE LOWEST TEMPERATURE		AT END OF REWARMING	2 HOURS AFTER PERFUSIONS
		TEMP.	THROMBOCYTES		
1	131	14.7	128	130	116
2	105	5.8	47	—	85
3	162	7.5	81	—	155
4	204	7.8	34	124	176
5	62	10.0	67	136	159
6	230	10.0	63	—	157
7	189	10.0	88	210	189
8	212	10.0	75	170	113
9	149	10.0	54	129	—
10	249	—	—	196	225
Mean values	169	9.5	71	109.5	137.5

The Red Blood Corpuscles (Table VIII).—The red blood corpuscles were counted before, during the cooling period, during the rewarming period, after the end of perfusion, and 2 hours after the perfusion. There were no significant changes either in the animal experiments or in human beings.

The Hematocrit.—There was no significant change in the hematocrit during the performance of deep hypothermia. In the only case in which a drop from 74 down to 47 per cent was noted was in a very cyanotic patient with tetralogy of Fallot.

The Hemoglobin.—No significant change in hemoglobin concentration was encountered during deep hypothermia.

The White Blood Corpuscles.—The white blood corpuscles, however, showed a significant decrease during the lowest temperature at deep hypothermia. At the end of the rewarming period, however, the number of white blood corpuscles

TABLE VIII. VALUES BEFORE, DURING, AND AFTER DEEP HYPOTHERMIA

	MEAN VALUES			
	BEFORE	AT LOWEST TEMP.	AFTER	2 HOURS AFTER
Red blood corpuscles (in millions)				
Patients	5.2	4.8	4.8	4.7
Dogs	5	5.7	5.7	—
Hematocrit (%)				
Patients	46.1	43.2	43.4	43.8
Dogs	48.5	51.2	50	55
Hemoglobin (%)				
Patients	89.3	84.7	86.1	87.8
Dogs	103.2	106.8	106.4	119
White blood corpuscles (in thousands)				
Patients	7.456	4.889	11.414	13.500
Dogs	10.125	3.425	4.034	14.600

were at about the same level as before the perfusion and 2 hours later a significant increase in the number of white blood corpuscles had occurred. These experiences are summarized in Table VIII.

The Acid Base Balance During Deep Hypothermia (Table IX).—The oxygen tension increased during the cooling as the oxygen requirement of the body decreased and it was highest before the arrest. After the arrest there was usually some oxygen debt that had to be paid before normal oxygen tension was reached again. At the end of the rewarming there was always an oxygen tension significantly above the normal. Two hours after the completion of the operation the oxygen tension was normal in all cases.

TABLE IX. THE CHANGES IN pO_2, pCO_2, pH, AND HCO_3 DURING AND AFTER DEEP HYPOTHERIMA

	BEFORE	AT LOWEST TEMPERATURE		AT END OF REWARMING	2 HOURS AFTER
		BEFORE ARREST	AFTER ARREST		
pO_2	88	162.5	82.6	115.6	97.1
pCO_2	36.2	37.5	39.4	29.3	32.8
pH	7.47	7.42	7.35	7.49	7.42
HCO_3	25.5	23.2	20.5	21.9	21.8

The carbon dioxide tension hsowed some elevation at the end of the arrest, but all values were within normal limits during the hypothermia.

The pH showed a tendency to alkalosis during the cooling period when the body was loaded with oxygen. At the end of rewarming and 2 hours after completion of the operation there was a normal pH in all cases but 1, Case 4. In that case, a pH of 7.10 was explained by a very poor perfusion due to an abnormal venous return of the right pulmonary veins into the right atrium with an intact atrial septum. As the methods for determination of pH and pCO_2 under deep hypothermia are not accurate, the conclusions are drawn on the values obtained after rewarming.

The Standard Bicarbonate.—There was a slight decrease in standard bicarbonate during the long period of arrest. Two hours after the end of operation

there was always a normal standard bicarbonate in all cases except Case 4, in whom an extreme metabolic acidosis occurred due to an intact atrial septum with abnormal venous return. This has been one of the most important reasons for favoring deep hypothermia with extracorporeal circulation to the use of an oxygenator. With the latter, after a long perfusion and cardiac arrest, there will be some cases of metabolic acidosis due to the perfusion per se. A metabolic acidosis has not been observed in deep hypothermia with a cooling down to 10° C. and with a flow during the cooling period of approximately 50 c.c. per kilogram of body weight.

Oxygen Consumption (Table X).—The total oxygen consumption is naturally small at the low temperatures and from the data so far obtained it does not seem to be worthwhile going below a temperature of 10° C. in the esophagus. Some examples of the oxygen content during the cooling period are summarized in Table X. Although at an esophageal temperature of 20° C. the color of blood in the line to the femoral artery and the pulmonary artery are about the same, it is necessary to lower the temperature to 10° C. before the body is loaded sufficiently with oxygen to withstand a circulatory arrest of 45 minutes.

TABLE X. THE OXYGEN CONSUMPTION IN MAN DURING DEEP HYPOTHERMIA*

PATIENT'S WEIGHT (KG.)	TEMPERATURE (°C.)	VOLUME PER CENT O_2		TOTAL OXYGEN CONSUMPTION (ML./MIN.)
		ARTERY	VEIN	
26.5	17	18.1	15.2	32.3
	11	18.4	17.95	5.5
	10	18.6	18.45	1.8
50	19	21.1	19.8	32
	15	21.6	21.3	7.5
	12.5	21.8	21.7	2.5
	10.2	22.15	22.10	1.25
19.6	12	17.9	17.5	6.8
	10	19.8	19.7	0.8
15.4	13.5	17.55	16.8	5.6
	10.5	18.88	18.48	3

*Measured by the difference in vol. % O_2 in blood from the cannula in the femoral artery and from the superior vena cava during total body perfusion at a known flow.

DISCUSSION

A heat exchanger for deep hypothermia is presented. The advantages of deep hypothermia with extracorporeal circulation without an oxygenator follow.

1. There is less blood trauma and less hemolysis.

2. The oxygenation in the patients' own lungs is better than in any oxygenator. No postoperative metabolic acidosis has occurred, therefore, unless there has been a very poor perfusion due to technical faults or anatomic variations, or cardiac standstill before the cooling period could begin.

3. During circulatory arrest in deep hypothermia, the myocardium is better protected than during an anoxic or potassium arrest. In the animal experiments, less incidence of tricuspid insufficiency, as a result of myocardial

impairment, was found after arrest at low temperature when compared with other types of cardiac arrest, which is especially important in cases of aortic valvular disease.

4. The surgical procedure is significantly facilitated and can be completed in a flaccid heart without any blood returning through the bronchial circulation.

5. The safety margin is increased. In case something goes wrong or the catheter slips out, the circulation can be completely arrested and there is enough time at the low temperature to correct the fault. In 1 patient, it was necessary to exchange the catheter draining the right atrium for a larger one when it was found that a much higher flow in the right circulation was needed than in the left due to abnormal return of pulmonary veins from the right lung with intact atrial septum.

6. There is better blood volume control, as a closed system is used, and there is no coronary perfusion and no loss of blood through the coronary suction system.

7. Cardiac arrest can be prolonged. A cardiac arrest of 45 minutes will not impair the myocardium and if a longer cardiac arrest is needed it is necessary only to replace the catheter and to perform a second perfusion with cold blood for 15 minutes to allow a second occlusion time long enough to complete the operation. The longest period of complete occlusion with success has been 47 minutes. In 1 patient, 70 minutes were necessary which caused brain damage. Therefore the maximum time for occlusion should be between 45 and 50 minutes. There seems to be no advantage to lowering the temperature still further as the accident of brain damage occurred after 70 minutes of occlusion at 5.8° C.

In the first series of 10 clinical cases, 6 patients survived the operation. Three died of brain damage (Table XI).

The patients accepted have had ventricular septal defect, cyanotic tetralogy of Fallot, septum primum defect, and infundibular stenosis. The fourth patient who died had ventricular septal defect + infundibular stenosis + valvular stenosis + abnormal venous return from the right lung with intact atrial septum. It was not possible in his case to diminish the pressure in the right ventricle to more than 80 mm. Hg, as the stricture in the main pulmonary artery, peripheral to the valvular stenosis, was 2 cm. long and there were further multiple strictures in the smaller pulmonary arteries. The patient was considered inoperable. The method has not been used for ordinary cases of atrial septum secundum defects with or without abnormal venous return. These patients are operated upon under surface cooling at a temperature of 30° C.

The disadvantages of the use of deep hypothermia without an oxygenator in the extracorporeal circulation follow.

1. There is a time limit of 45 minutes of the circulatory arrest in adult patients.

2. Brain damage has been encountered in 3 children. I believe this brain damage is caused by a thrombus formation of aggregated thrombocytes and

TABLE XI. THE COMPLICATIONS ENCOUNTERED IN THE FIRST CLINICAL CASES UNDERGOING OPEN-HEART SURGERY WITH DEEP HYPOTHERMIA UTILIZING EXTRACORPOREAL CIRCULATION WITH HEAT EXCHANGER

CASE NUMBER	DIAGNOSIS	ESOPHAGEAL TEMPERATURE AT ARRIVAL (°C.)	TIME OF CIRCULATORY ARREST (MIN.)	COMPLICATION	RESULT
1	IS,* reoperation	14.7	25	0	Survival
2	Tetralogy of Fallot	5.8	70	Block + brain damage + wound infection	Died of brain damage
3	IS + pulmonary stenosis + ASD†	7.5	47.5	0	Survival
4	VSD‡ + IS + pulmonary valvular stenosis + multiple peripheral pulmonary stenosis + abnormal venous return	7.8	49		Died (inoperable)
5	ASD (secundum) reoperation	10.0	21	0	Survival
6	Total abnormal venous return + ASD (secundum)	10.0	38	0	Survival
7	VSD	10.0	44	Block + brain damage	Survival
8	Ostium primum defect, reoperation	10.2	27	Block + pulmonary edema	Survival
9	Tetralogy of Fallot	10.0	50	Block	Died of brain damage
10	Ostium primum with cleft mitral valve	10.0	41	Brain damage	Died of brain damage

*IS = Infundibular stenosis.
†ASD = Atrial septal defect.
‡VSD = Ventricular septal defect.

white blood corpuscles, which largely disappear from the circulation at a low temperature. During the rewarming, the aggregated thrombocytes and white blood corpuscles return to the circulation and may have occluded the circulation in certain areas in the brain for some time, with a focal necrosis as a result. At the present time, I consider the method contraindicated for children. We have not been able to prevent this thrombocyte agglutination by increased heparin dose (5 mg. per kilogram) or by dilution of blood with low molecular macrode.

3. The method of using two parallel pump systems is much more difficult to handle than an ordinary pump-oxygenator with a heat exchanger.

4. The method is considerably more time consuming.

SUMMARY

Deep hypothermia with extracorporeal cooling without an oxygenator, according to Drew, has been used in 17 clinical cases and compared with the pump-oxygenator system. After this comparison, the original deep hypothermia method has been abandoned.

The ordinary pump-oxygenator (with the spinning disc oxygenator) is preferred at normal temperature in most cases, but combined with deep hypothermia in aortic valvular disease to protect the myocardium and permit longer perfusions. In children, deep hypothermia is considered contraindicated due to the risk of brain damage. Therefore, in children, the myocardium is protected by local hypothermia, achieved by surrounding the heart with plastic bags with ice* or by isolated coronary perfusion with cold blood.

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*After acetylcholine arrest.

STUDIES WITH A CELLULOSE MEMBRANE OXYGENATOR

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INTRODUCTION

THE DIFFUSION of small molecules and ions from one fluid to another through a semipermeable membrane and its clinical utility in therapeutic hemodialysis is now amply documented. However, the practicality of gas transfer under similar conditions has not been generally appreciated and its clinical value has, therefore, not been fully studied. Many observers have commented on the partial oxygenation of blood during the hemodialysis of cyanotic patients.

This capability of the dialyzer to transfer respiratory gases to and from blood, combined with its action as an electrolyte stabilizer and as an excellent heat exchanger, would appear to be valuable in a number of diseases and clinical situations. With this in mind, an experimental oxygenator and carbon dioxide exchanger,* patterned after the parallel-flow, straight tube hemodialyzer[1-3] was designed and constructed by Dr. Arthur E. MacNeill to determine the performance of this design with respect to respiratory gas transfer.

THE EXPERIMENTAL OXYGENATOR

The apparatus (Fig. 1) consists of 40 flat tubes of regenerated cellulose† about 0.0015 in. wall thickness when wet, arranged in parallel with interposed nylon screens of slightly greater width. The blood film is held to approximately 0.018 cm. thick in each tube. The tubes connect to a common channel at each end of the apparatus by means of uniquely designed Teflon inserts. The transparent Plexiglas case enables the investigator to observe the blood-filled cellulose tubes and the flow of the gas transferring dialyzing bath. The unit contains 3 square meters of membrane area and is designed for blood flow rates of 1,200 c.c. per minute. The blood pathways contain a total of 280 c.c. of blood for each 3 square meters of area.

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*(MacNeill Model XII-B-40-36.)

†Visking "No-Jax" Sausage Casing (36/32 in. size, 0.0008 in. dry thickness).

A dialyzing bath solution (Table I) is equilibrated with an oxygen–carbon dioxide atmosphere by spraying and agitating it with an $O_2 : CO_2$ mixture (95.5) flowing at the rate of 3 to 5 liters per minute. The container of this bath is adequately vented to allow the escape of the carbon dioxide into the atmosphere, thus maintaining physiologic levels of carbon dioxide and providing about 2 vol. per cent of oxygen dialyzing fluid with its dissolved gases to be propelled crosswise to the long axis of the cellulose tubes through the mesh of the nylon screens at a rate of 40 to 50 liters per minute by a centrifugal pump (Fig. 2).

The blood pumps[4] used in these experiments are atraumatic pumps also designed by Dr. MacNeill. Their gentleness toward blood cellular elements

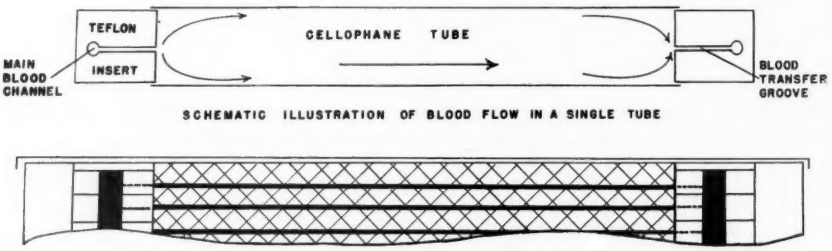

Fig. 1.—Diagrammatic representation of longitudinal cutaway side view of the interior of the oxygenator.

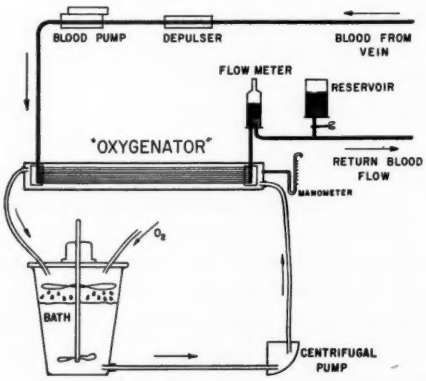

Fig. 2.—Diagrammatic representation of the bath and blood circuit and the manner in which the dialyzing solution is saturated with oxygen.

TABLE I. COMPOSITION OF THE DIALYZING BATH

	mEq./L.	MG. %
Sodium	140	
Potassium	4.5	
Calcium	4.5	
Magnesium	1.0	
Chlorine	120	
HCO_3	27.0	
Glucose		100

has been demonstrated on several occasions in patients dialyzed for renal shutdown or intoxications due to various poisons.[5] Plasma hemoglobin determinations during such clinical procedures showed a slow increase from less than 1.8 mg. per cent to a maximum of 6.5 mg. per cent in 8 hours.

PROCEDURES

I. *Oxygenation.*—Vein-to-vein and vein-to-artery perfusions (the latter requiring 2 blood pumps) at different rates of flow were performed on 16 mongrel dogs weighing from 10 to 25 Kg. (Fig. 2). The dogs were anesthetized with 1 c.c. per pound of body weight of a 2.5 per cent sodium pentobarbital solution and maintained on a respirator. Heparin, at 1.5 mg. per kilogram of body weight and 15 mg. per 500 c.c. of priming blood, was administered just before cannulization. In vein-to-vein perfusions, the blood was drawn from the inferior vena cava via a cannula inserted through one femoral vein. Blood was returned into the external jugular vein. In vein-to-artery perfusions, blood was drawn from both venae cavae by cannulas threaded through the right arterial appendage following a right thoracotomy, and returned into the right common carotid artery. Blood samples were drawn from the Tygon blood tubes before and after passing through the oxygenator. The oxygen and carbon dioxide content was determined by a method of Van Slyke.[6] Recirculation of blood was utilized in some of these perfusions to determine the rate of oxygen transfer at higher saturation levels. Two to four samples at various flow rates were taken during each perfusion. The amount of oxygen delivered per square meter of membrane used per minute was computed as follows:

$$\frac{\text{A-V diff. (vol. \%)} \times \dfrac{\text{flow rate (c.c./min.)}}{100}}{\text{Membrane area used (M.}^2\text{)}}.$$

RESULTS

I. *Oxygenation.*—The amount of oxygen picked up by a unit of blood in one pass through the oxygenator is dependent on the length of time the blood is in contact with the solution-bathed membranes and, therefore, was generally higher at the low flow rates. However, the total amount of oxygen delivered per square meter of cellulose membrane was greater at higher flow rates as indicated in the scattergram (Fig. 3). This apparatus was designed for 1,200 c.c. per minute of blood flow. Therefore, in the low ranges of flow from 100 to 500 c.c. per minute, all the cellulose tubes may not have had equal flows although they remained open. Oxygen transferred at both low and high saturation levels is illustrated in Fig. 4. The total amount of oxygen transferred through one square meter of cellulose per minute (Table II) averaged 5.4 c.c. Preliminary results, not included in the table, were inconsistent in the first perfusion studies before the numerous factors influencing gas exchange were properly controlled.

Carbon dioxide determinations on the same blood samples showed varying amounts transferred between blood and bath solution to maintain normal blood levels. The facility with which these dialyzing membranes allow the transfer of carbon dioxide is of great significance.

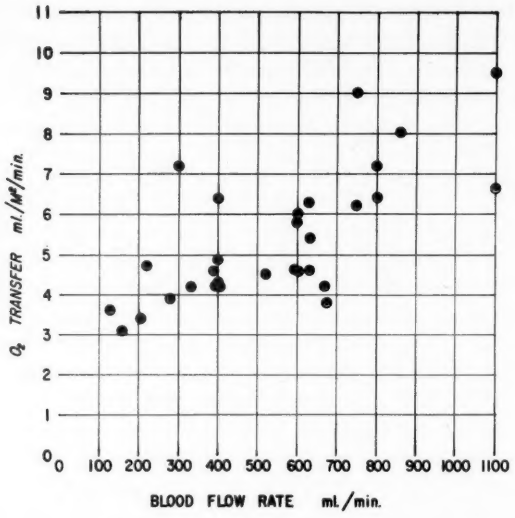

Fig. 3.—Scattergram illustrating oxygen transfer at various rates of blood flow.

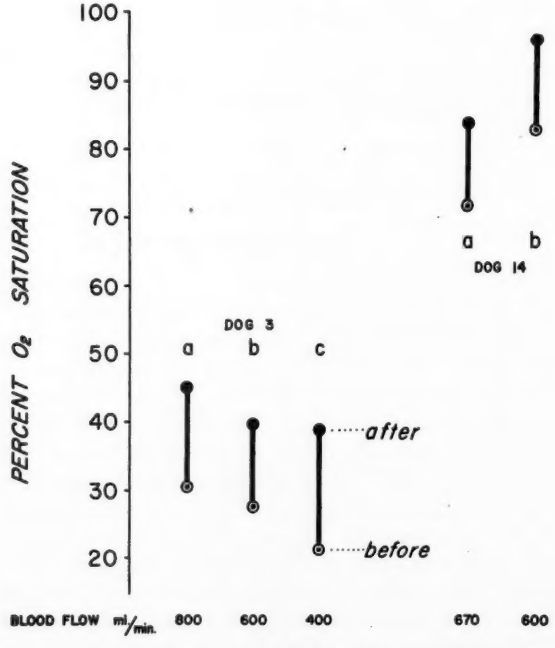

Fig. 4.—Comparison of oxygen transfer through the cellulose membrane oxygenator at both low and high oxygen saturation levels.

TABLE II. PERFUSION RESULTS AFTER ONE PASS THROUGH OXYGENATOR WITH CALCULATION OF OXYGEN TRANSFER PER SQUARE METER OF CELLULOSE MEMBRANE

DOG	RUN	FLOW RATE OF BLOOD (ML./MIN.)	BLOOD O_2 INCREASE VOL. %	O_2 TRANSFERRED (ML./M.^{2}/MIN.)
3	a	800	2.7	7.2
	b	600	2.3	4.6
	c	400	3.2	4.2
4	c	400	4.3	4.3
	d	600	2.9	5.8
5	a	400	4.8	6.4
	c	400	3.2	4.2
6	b	631	2.6	5.4
7	a	390	3.8	4.6
8	a	300	2.4*	7.2
	b	750	1.2*	9.0
9	a	675	1.7	3.8
	b	160	5.9	3.1
10	b	1,100	2.6	9.5
	c	1,100	1.8	6.6
11	a	400	3.7	4.9
	b	220	6.5	4.7
12	a	600	3.0	6.0
	b	280	4.2	3.9
	c	130	8.3	3.6
13	b	206	5.0	3.4
	c	333	3.8	4.2
14	a	670	2.1	4.2
	b	600	2.3	4.6
	c	630	2.0	4.6
15	a	750	2.5	6.2
	b	860	2.8	8.0
16	a	520	2.6	4.5
	b	630	3.0	6.3
	c	800	2.4	6.4

*Only 1 square meter of cellulose membrane was used. In remainder of runs, 3 square meters of cellulose membrane were used.

DISCUSSION

Oxygenation of the Total Circulation.—The various heart-lung machines currently used today have been designed solely for the purpose of oxygenation and carbon dioxide extraction. Except for a heat exchanger[7] which only recently has been added to some circuits for temperature regulation, no other reliable measures have been devised to prevent or correct some of the more important problems accompanying the use of these oxygenators. The most serious of these problems are electrolyte and pH abnormalities. It would seem logical, then, to seek an oxygenator that will not only deliver oxygen and extract carbon dioxide but will also maintain normal chemical and metabolic equilibrium during cardiopulmonary bypass. Similarly, anesthetic solutions, particularly Anectine and the barbiturates, might be administered through such an apparatus to maintain proper concentrations in the blood.

This experimental dialyzer-oxygenator can be expected to perform all of these useful functions. In addition, hemolysis is negligible because of the quality of the blood pumps used and because recirculation is not essential except for priming purposes. (The 3 square meter unit alone primes with 280 c.c. of blood.)

With respect to respiratory gas exchange, these perfusion studies have indicated that a dialyzer-oxygenator, built with a total area of 12 square meters of cellulose membrane, should be capable of maintaining adequate respiratory gas exchange for a child up to 10 to 15 kilograms in weight. Because it is known that the oxygen requirements decrease with lower temperatures,[8] such apparatus might be used on larger patients when combined with hypothermia. Furthermore, the maintenance of normal blood chemistry, carbon dioxide levels, pH, and proper dextrose levels may enable the subject to tolerate a greater degree of tissue hypoxia or incomplete oxygenation. Investigative studies are now being carried out with this problem in mind.

One problem which has yet to be investigated is the possibility that an oxygenating surface of 12 square meters of cellulose may be too large a dialyzing area for a child. Under such circumstances, essential trace substances might be extracted from the child's blood, with adverse results; or adsorption of either diffusible or nondiffusible substances to the extensive membrane surface may occur, leading to similar consequences. These possibilities should be investigated carefully before clinical trials of such large area dialyzer-oxygenators are attempted, as clinical experience with dialyzing membranes has not exceeded 25,000 square centimeters to date.

Oxygenation of the Partial Circulation.—Decompression by phlebotomy in addition to digitalization and other resuscitative measures in the emergency management of acute heart failure is a time-recognized procedure. Recently, shunting of blood from vein to artery, utilizing a pumping system, alone or in combination with a portable oxygenator, for the same purpose, has been reported[9] with promising results. A version of our experimental oxygenator might be similarly employed with the advantages of combined partial oxygenation, dialysis, temperature regulation, and ultra-filtration. There would be few contraindications to prolonged or repeated perfusions with the use of this unit. Use of this equipment as an aid in the emergency management of acute (temporary) pulmonary insufficiency such as occurs following pneumonectomy, in patients with borderline pulmonary function, in infiltrating parenchymal disease, pulmonary edema, emphysema, and acute laryngo-tracheo-bronchitis of infants, can also be contemplated.

SUMMARY AND CONCLUSIONS

Perfusion studies on mongrel dogs have been performed to determine the capabilities of a special parallel flow straight tube hemodialyzer as an oxygenator and carbon dioxide extractor.

The oxygenator tests have shown that 5.4 c.c. of oxygen can be transferred from an oxygen-saturated dialyzing bath solution to blood per square meter of cellulose surface per minute, and that a unit containing 12 square meters of membrane area should be capable of supplying the entire oxygen requirements of a child up to 10 to 15 kilograms in weight.

Its use in the emergency management of cardiac failure and acute (temporary) pulmonary insufficiency is postulated, based on performances demonstrated in these laboratory studies.

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VARIATIONS OF THE THROMBIN TIME IN CERTAIN PATIENTS UNDERGOING OPEN-HEART SURGERY: DISCUSSION OF ITS PROGNOSTIC SIGNIFICANCE

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FIBRINOLYSIS and the appearance of an anticoagulant as measured by the thrombin time were reported by us to be two major clotting derangements which may occur during cardiac surgery with the use of a pump-oxygenator.[1] It was also noted that the presence of the anticoagulant(s) was most readily demonstrable when cardiovascular difficulties were encountered during the operative procedure or when such complications developed relatively shortly after surgery. Since that time special attention has been given to changes in thrombin time in patients undergoing cardiac surgery combining, in most instances, a pump-oxygenator with hypothermia. As a result of these observations it is considered that serial determinations of the thrombin time may be of prognostic value. Marked elevation of the thrombin time was frequently observed before a clinical manifestation of cardiovascular dysfunction occurred, and it was also observed that an elevated thrombin time before surgery coincided with a higher surgical risk. It is, therefore, believed that a marked increase in the thrombin time may reflect a disadvantageous alteration in the systemic response of the cardiac patient to surgical stress. The main emphasis of this paper is to demonstrate the possibility that there exists a relationship between the fluctuations in the clotting system as measured by the thrombin time and the development of cardiovascular complications, such as: total or partial heart block, auricular or ventricular fibrillation, severe drop in blood pressure, and reversible cardiac arrest.

The data presented are based on observations on 27 unselected patients undergoing open-heart surgery. The thrombin times were measured as indicated earlier.[1] Our original goal was to study fibrinolysis and some of the essential findings have been reported previously. A rather unexpected by-product of the study was the gross abnormalities of the thrombin time observed under these circumstances which initiated further investigation. Fig. 1 illustrates the results. It shows the mean thrombin time of these patients at various

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intervals before and during surgery. The intervals were: (a) control, either before induction of anesthesia or the day before operation; (b) after induction of anesthesia; (c) immediately after extracorporeal circulation and protaminization; (d) approximately 30 minutes after protaminization; and (e) approximately 1 hour after protaminization, and, if indicated, at successive intervals. The normal thrombin time is about 12 seconds, as represented by the dotted line in Fig. 1. The numerals below the histograms indicate the number of patients from whom the average values were obtained. The set of histograms on the

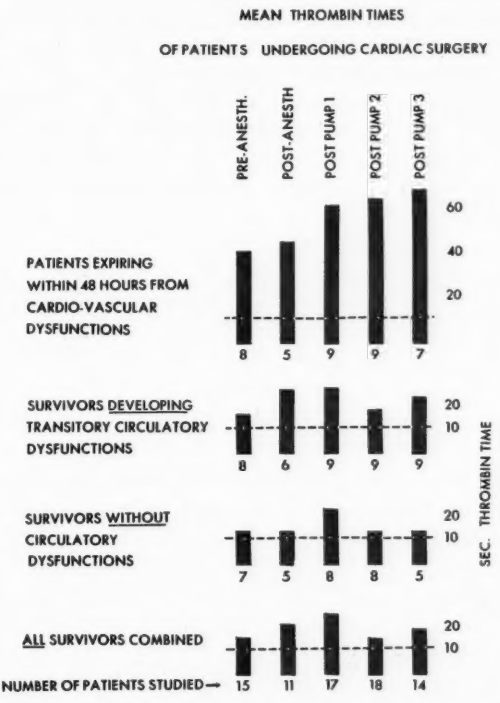

Fig. 1.—Mean thrombin times of surviving and nonsurviving patients during various phases of cardiac surgery. Dotted line represents normal values.

bottom of the figure shows the serial thrombin times for all patients surviving the procedures. It can be seen that all their thrombin times are definitely longer than normal. If, however, the survivors are separated in two groups, one consisting of patients exhibiting no particular cardiovascular disturbances during and after the procedure, and the other consisting of those who developed dysfunction during the operation or immediately thereafter, then it becomes apparent that the patients who developed transitory circulatory dysfunctions are the ones responsible for the rise in the mean serial thrombin times of all survivors. This is indicated by the second and third set of histograms on the bottom of the figure.

If the thrombin times of patients dying from cardiovascular complications within a few days are computed, the picture changes drastically. This computation has been done in the upper set of histograms of Fig. 1. The thrombin times in this group of patients were extremely long and, in several instances, no clot at all could be obtained. For the calculation of our average values, incoagulability within 5 minutes was set at 120 sec. thrombin time. The incoagulability was due to an inhibitor and not due to afibrinogenemia as demonstrated by a mixing test with normal plasma and the easy obtainability of an euglobulin clot which contains only about 25 per cent of the total plasma fibrinogen. Note the particularly gross deviations from normal during the post-pump phase. It is essential to emphasize that, in patients dying within 48 hours, the thrombin time was frequently already elevated in the control values and/or in the sample drawn after induction of anesthesia. In general, it was noted that in most of our patients exhibiting cardiovascular dysfunction during or after surgery, the elevation of the thrombin time could be demonstrated *before* the clinical symptoms became apparent (within 48 hours). Table I shows this.

TABLE I

	SURVIVORS	NONSURVIVORS
Number of patients	9	9
Patients with thrombin time above 24 sec.		
Before surgery	0	6
After surgery	2	7
Before or after surgery	2	9

Of 9 surgical patients dying from cardiovascular complications, 6 exhibited a prolongation of the thrombin time to double or more of normal values *before* the heart was opened, in contrast to 9 patients with no complication who did not show this abnormality. In 9 patients who succumbed, all had at least one very gross abnormality (above 40 sec.) of the thrombin time during the period of observation in contrast to only 2 of a group of 9 who maintained stable circulatory systems.

The group of survivors in which some cardiocirculatory disturbances developed is in an intermediate position, which becomes apparent when the percentage of the thrombin time determinations above 24 seconds is calculated for each group. The percentages are: survivors without dysfunction, 5.7 per cent; survivors with dysfunction, 25 per cent; nonsurvivors, 64 per cent.

The significance of the thrombin time is obvious when the results from the patients in whom it was possible to determine the thrombin time before *and* after induction of anesthesia, but before actual surgery, are studied (Table II). It can be seen that a prolonged thrombin time before anesthesia (control value) signifies a poor prognosis and that a rise of the thrombin time after induction of anesthesia also carries a serious prognosis.

Figs. 2 through 6 demonstrate our findings in individual examples. The arrangement of all the figures is almost identical. The fibrinolytic activity is

estimated with the euglobulin technique, the only one which allows a quick measurement of fibrinolytic activity in blood uncoagulable due to the presence of clotting inhibitors.[2] The values are expressed in minutes as euglobulin lysis time, the normal values being above 120 minutes. The thrombin times are expressed in seconds, and the urokinase values in our laboratory units (specific gravity coefficient); also indicated is the surgical phase at which the samples were drawn and these data are correlated with the actual time.

Fig. 2 represents a patient who was operated upon without complications with the use of hypothermia combined with a pump-oxygenator for the suture closure of an interventricular septal defect. The euglobulin lysis time exhibits increased lysis of the control plasma, a tendency that has been frequently

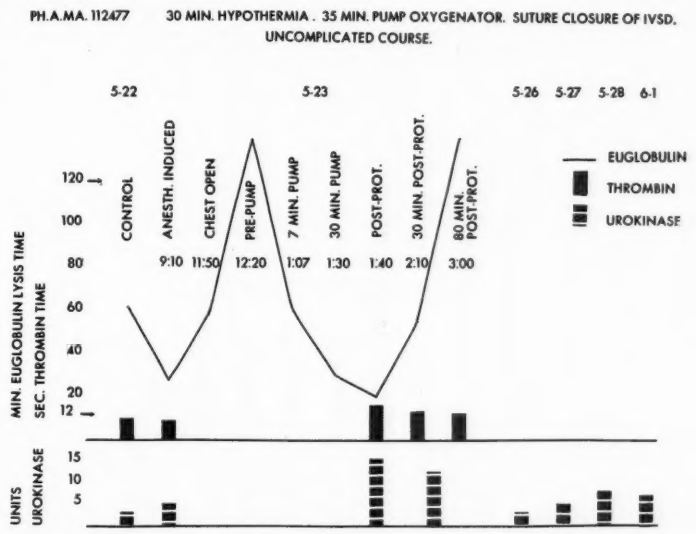

Fig. 2.—Trend of thrombin time, fibrinolytic activity, and urokinase excretion of a patient operated upon for suture closure of interventricular septal defect–30 minutes hypothermia, 35 minutes pump-oxygenator. No gross changes of thrombin time. *Note:* Increase of urokinase excretion during the second fibrinolytic phase.

TABLE II. RESULTS FROM 15 PATIENTS IN WHOM THE THROMBIN TIME WAS DETERMINED BEFORE AND AFTER INDUCTION OF ANESTHESIA
(9 PATIENTS ALIVE, 6 DEAD)

	NUMBER OF PATIENTS	ALIVE	DEAD	
Thrombin time *below* 24 sec.				
Before anesthesia	11	9	2*	18%
After anesthesia	8	7	1*	14%
Before *and* after anesthesia	8	7	1*	14%
Thrombin time *above* 24 sec.				
Before anesthesia	4	0	4	100%
After anesthesia	7	2	5	71%
Before *and* after anesthesia	4	-	4	100%

*The 2 patients in these groups who died, in contrast to the survivors, exhibited extreme prolongation of the thrombin time during the post-pump period.

observed. This is seen in children with congenital heart disease and is enhanced by induction of anesthesia. The increase in tendency to lysis disappears as anesthesia continues, reappears during the pump phase, is enhanced by protamine injection, and finally disappears completely. The urokinase excretion also shows the usual trend: an increase concomitant with the increased lysis tendency in the late pump phase and early post-pump phase, a decrease in the first postoperative days, and then a gradual return to normal. The thrombin time itself shows no particular rise except for the first post-protamine injection sample; but here, the presence of heparin traces from the previous heparinization cannot be absolutely excluded.

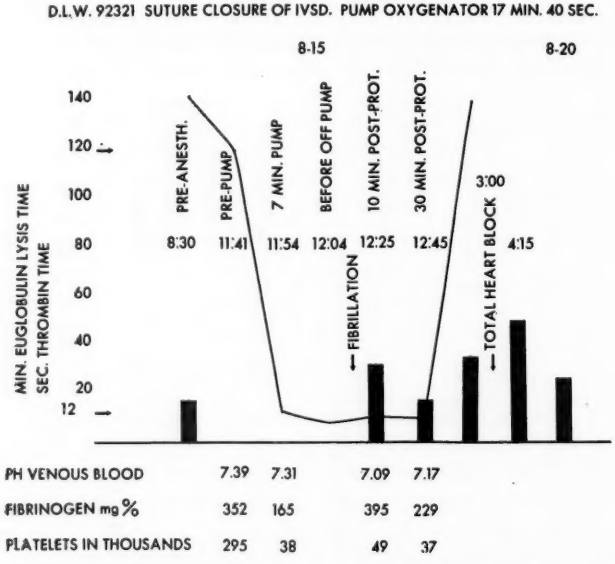

Fig. 3.—Trend of thrombin and fibrinolytic activity of a patient operated upon for suture closure of interventricular septal defect. *Note:* Increase of thrombin time, appearance of heart block, and strong fibrinolytic reaction combined with acidosis. Pump-oxygenator: 17 minutes.

Fig. 3 represents the data from a surviving patient who exhibited ventricular fibrillation during the closure of his septal defect and developed a total heart block during the immediate postoperative period. It can be seen that the thrombin times are considerably prolonged and they show a definite increase *before* the appearance of the heart block. Note also the very marked increase in fibrinolytic tendency which is sustained by acidosis, an observation which has previously been described by us.[1]

The increase in thrombin time can reach quite extraordinary proportions. Figs. 4 through 6 are shown as instructive examples. Fig. 4 gives the data from a patient with the tetrology of Fallot. He was operated upon with the use of the pump-oxygenator for suture closure of an interventricular septal defect and resection of an infundibular stenosis. The preoperative thrombin times were prolonged and then became indeterminable after the pump phase.

At that time, oozing was noted; however, there was no increase in fibrinolytic activity. Three grams of fibrinogen were given, the oozing subsided, and the thrombin time became measurable again. Soon it returned to immeasurable values and the oozing started again. Following this, a complete atrioventricular block developed and the thrombin time remained immeasurable during this period. In vitro, 15 mcg. of protamine sulfate per cubic centimeter added to the citrated plasma of this patient shortened the thrombin time considerably. Four hours after the last blood specimen was drawn, the patient died. It can be seen from Fig. 4 that the increase in thrombin time anteceded the cardiovascular disturbances. There was no fibrinolysis whatsoever and the incoagulability of the patient's blood was not due to afibrinogenemia but due to a very marked increase of thrombin inhibitor.

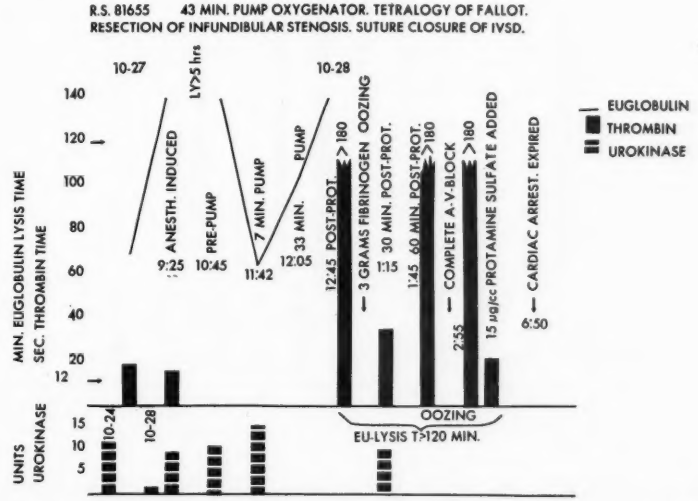

Fig. 4.—Tetralogy of Fallot. Patient operated upon for infundibular stenosis and suture closure of interventricular septal defect. Trend of thrombin time, fibrinolytic activity, and urokinase excretion. *Note:* Gross increase of thrombin time before oozing and atrioventricular block. Pump-oxygenator: 43 minutes.

A comparable situation prevailed with the patient whose data are shown in Fig. 5. The diagnosis and the surgical procedure were similar to that in the previous patient. His thrombin times were extremely prolonged from the very beginning. The shortest value during the operative period was observed 5 minutes after injection of protamine. Thereafter, however, the thrombin time again rose to immeasurable values. About 12 hours after surgery, the patient had a cerebral vascular accident, the nature of which could not be determined. As a result of this accident, the patient had to be put in a respirator. He never regained consciousness and died 6 days later. Again in this patient, the rise of the thrombin time preceded the circulatory dysfunction. The postoperative urokinase values in this patient did not return to normal after the immediate postoperative drop, as they do in patients with normal post-surgical recovery.

Fig. 6 shows the data from a third patient with tetralogy of Fallot. In this case, hypothermia alone was used. The patient had a prolonged control thrombin time which rose to very high values after induction of anesthesia. It became immeasurable after occlusion of the circulation and remained that way. The appearance of these high values preceded a series of cardiac arrests. The patient died 2 days later. There was an increase in the fibrinolytic activity during surgery but, in contrast to surviving patients, the urokinase values of this patient dropped continuously during and after surgery until his death.

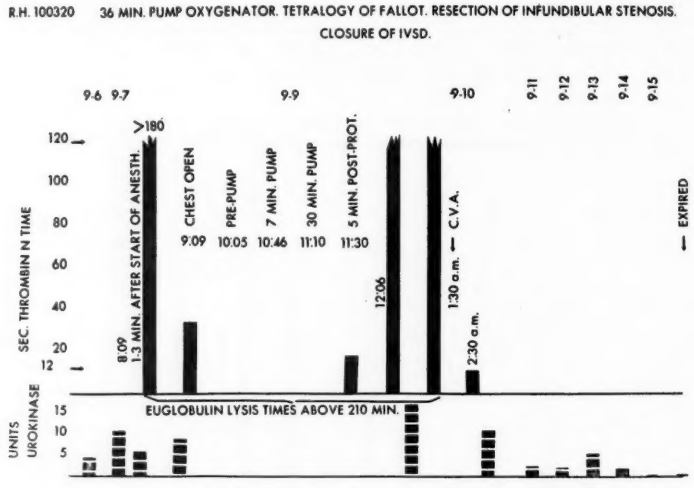

Fig. 5.—Tetralogy of Fallot. Patient operated upon for resection of infundibular stenosis and closure of interventricular septal defect. Trend of thrombin time and urokinase excretion. No increase in fibrinolytic activity. *Note:* Gross increase of thrombin time before surgery and reappearance of gross increase of thrombin time before cerebral vascular accident. Pump-oxygenator: 36 minutes.

The prolongation of the thrombin time which has been observed is due to a thrombin inhibitor. This is demonstrated by determining thrombin times in mixtures of the patient's plasma with normal plasma which results in a prolongation of the thrombin time of the normal plasma. Examples are shown in Table III.

Mismatched transfusions are another cause of a sudden rise of the thrombin time.[3] Here again, it was observed that the thrombin time of normal plasma

TABLE III. INCREASES IN THROMBIN TIMES OF NORMAL PLASMA BY ADDITION OF PATIENT'S PLASMA: TWO EXAMPLES

	PER CENT CONCENTRATION OF PLASMA		THROMBIN TIME (SEC.)
	PATIENT	NORMAL	
Case 1	100	—	180
	—	100	11
	25	75	17
	75	25	37
Case 2	100	—	240 +
	—	100	7
	40	60	240 +
	20	80	20

was prolonged by the addition to it of the plasma of the patient. The release of a "heparinoid" anticoagulant was studied extensively with the thrombin time in dogs exposed to mismatched transfusions by McKay and his colleagues.[4]

A marked prolongation of the thrombin time was also seen by us, combined with an increase in fibrinolytic activity and oozing tendency, in a patient being prepared for portocaval shunt, and in patients with severe pulmonary lung embolism.

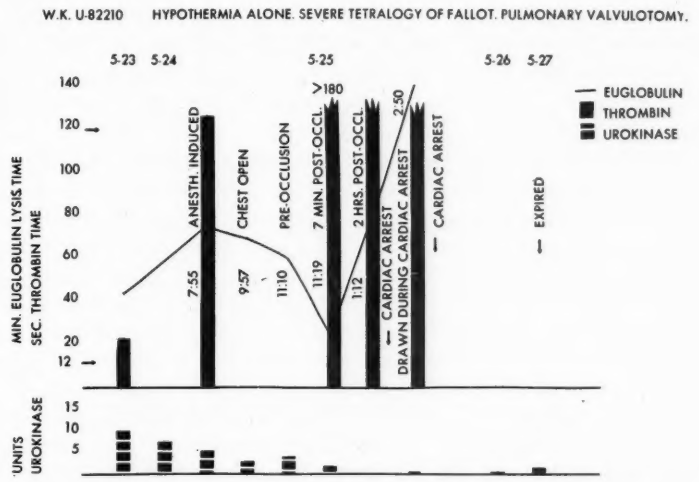

Fig. 6.—Tetralogy of Fallot. Patient operated upon for pulmonary valvulotomy under hypothermia. *Note:* Increase thrombin time in control sample and gross increase during anesthesia and surgery preceding a series of cardiac arrests. Steady drop of urokinase excretion until death.

DISCUSSION

The immediate problem raised by these observations is the nature of the anticoagulant causing the clotting defect. It is not yet possible to say whether this substance is heparin, or not. It is sometimes neutralized by protamine both in vitro and clinically but, on other occasions, protamine is quite ineffectual and excessive quantities are required for neutralization of the thrombin inhibitor in vitro. Possibly two related compounds are involved; for instance, heparin and Loeliger's[5] antithrombin V, which immediately neutralizes thrombin but is not neutralized by protamine.

It is well known that a variety of stimuli, including experimental shock, may trigger the release of heparin and related substances into the general circulation; but observations of the release of an anticoagulant during surgery in man are scant. Perlick[6] noted a marked increase in "heparin-antithrombin" levels during prostatectomy on hypotensive patients, but did not see this change in those operated upon without hypotension, although there was a release of "heparin-antithrombin" in patients with vasolability. Weiss[15] mentions 2 patients who presented a "heparin-like" syndrome after open-heart surgery with hypothermia and Muller[1a] reported on a patient who exhibited

a prolonged thrombin time which was not corrected by administration of protamine after disconnection of the pump-oxygenator. The plasma of this patient prolonged the thrombin time of normal plasma. We reported an increase of thrombin inhibitor in cardiac patients operated upon under hypothermia.[9] However, these increases were moderate compared with the ones previously reported and with those described in the present study of patients of a different type and operated upon with a different technique.

Experimentally, Lasch[7] demonstrated a marked release of heparin during the rewarming phase in hypothermic dogs undergoing heart surgery. Kolff and co-workers[8] observed in dogs a reappearance of delayed clotting several hours after protaminization and designated this phenomenon a "heparin-rebound" effect; but, these observations might well be related to the findings described here.

It has been reported that during the course of a variety of diseases, such as disseminated lupus erythematosus, metastatic carcinoma of the liver, cirrhosis of the liver, malabsorption syndrome, multiple myeloma, pre-eclampsia, and eclampsia, an anticoagulant may appear which produces a prolongation of the thrombin time accompanied by a hemorrhagic diathesis uncorrectable by the administration of protamine sulfate. (For literature, see Favre-Gilly and collaborators.[10]) In these diseases, the clotting defect appears gradually but, during surgery, it appears suddenly, suggesting the possibility of an abrupt release of the anticoagulant from storage organs. The same situation obtains in experimental anaphylactic shock during which an anticoagulant of antithrombin type is momentarily released which results in incoagulability and is accompanied by a reduction of the surface tension of the blood. If the shock is lethal, the anticoagulant can be demonstrated until the death of the animal. Near lethal Adrenalin injections produce the release of an antithrombin substance in contrast to small doses which enhance coagulation.[11] Pharmacologically, active compounds acting on the autonomic nervous system, as well as pain, mechanical stimulation of vagosympathetic or parasympathetic nerves, or of certain parts of the cortex, bring about a very swift change of the activity of a variety of clotting components.[12, 13] Increased sympathetic tone is likely to enhance the coagulation in contrast to vagus stimulation which exerts an inhibiting effect. Vagal tone tends to increase the heparin antithrombin. There are some contraindications in the literature which might be explained by the observation[13] that the changes in the activity of the coagulation factors are dependent upon the tonus of the autonomic system at the moment of stimulation.

Therefore, the release of thrombin inhibiting substances may depend upon the status of the autonomic nervous system of the patient. Certain changes in its reactivity may induce the release of inhibitors and simultaneously influence the cardiovascular system in such a way that it responds abnormally to surgical and other stresses. If this assumption is correct, our observation that increase in thrombin time heralds the cardiovascular disturbances might be explained on this basis. Interestingly enough, the highest preoperative

thrombin times were observed in patients with tetralogy of Fallot. De Sario[14] also found increased antithrombin activity in the patients with tetralogy of Fallot. There is frequently a high risk in operating on these patients.

Bleeding, itself, was a problem in only 2 of our patients and, therefore, is not an inevitable consequence of an elevation of the thrombin time. This phenomenon is more likely to occur when the inhibitor increase coincides with very marked fibrinolytic activity. Severe bleeding of this type was seen in 1 patient, reported in detail earlier.[1] A second patient (Fig. 4) exhibited a considerable oozing tendency concomitant with a very marked increase in thrombin time.

Bleeding may be treated by the use of fibrinogen and ACTH infusions, $CaCl_2$ and Adrenosem. Protamine may be tried but it occasionally enhances or initiates a fibrinolytic reaction. The maintenance of an adequate blood pressure by the adequate replacement of blood loss and other means is of crucial importance.

It would seem likely that, during the past, incoagulability of blood developing during surgery or under other circumstances may well have been misdiagnosed as afibrinogenemia, when, in reality, a strong thrombin inhibitor was present.

SUMMARY

Serial thrombin time determinations were done in 27 patients undergoing cardiac surgery. Twenty-six were operated upon with the pump-oxygenator, with or without hypothermia, and 1 with hypothermia alone. In the patients who died after the procedure, a marked elevation of the thrombin time was found in the control specimen, and a marked rise after induction of anesthesia, but before the surgery. A sudden rise of the thrombin time during the post-pump phase heralds cardiovascular dysfunction which may or may not lead to death. Postoperative death was associated with the greatest elevations of the antecedent thrombin times. The mechanism underlying these findings is discussed.

We wish to thank Mrs. Edith von Kaulla for her technical assistance in this study.

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TRAUMATIC ANEURYSM OF THE THORACIC AORTA SIMULATING COARCTATION

A Case Report

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New York, N. Y.

TRAUMATIC thoracic aneurysms have been described as a pathologic entity for many years[1-4] but only occasionally present as a surgically correctable lesion. This lesion has been encountered only twice among 126 patients with thoracic aneurysm operated upon at Presbyterian Hospital. During recent years, excisional therapy has proved increasingly safe and effective, emphasizing the need for increasing our knowledge of the clinical course of this entity.

The majority of patients receiving trauma sufficient to rupture the aorta die almost immediately. Attesting to this is the fact that the largest reported series of 72 traumatic aneurysms was among 7,000 consecutive autopies reported from the Chief Medical Examiner's office of New York City.[5] The fate of those patients who survive the initial aortic injury appears variable and for the most part unpredictable. Survival and the subsequent clinical course must depend upon the depth and size of the aortic tears and the ability of the residual media, adventitia, and adjacent structures to buttress the laceration and hematoma against constant aortic pressure.

The development of a widened mediastinum and clouding of the aortic knob, following severe chest trauma, should strongly suggest that rupture of the aortic wall may have occurred. The subsequent x-ray appearance of a bulging or double contour in the area of the aortic arch, during the first to fourth weeks following injury, is diagnostic of traumatic aneurysm, or, better termed, a false aneurysm. The subsequent course of these lesions has been difficult to evaluate but, based on a summary of available reports of patients surviving the first 10 hours after injury, approximately 40 per cent of these aneurysms rupture within the first 60 days (Table I). Steinberg[18] has recently emphasized that a certain number of these lesions become chronic, stable, and ultimately show calcification by roentgenogram. Unfortunately there is no satisfactory way to anticipate which of the acute lesions will become chronic and stable from

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those that will rupture. In the case to be presented, there developed a clinical picture associated with a traumatic aneurysm of the descending thoracic aorta that has not previously been described; an awareness of this sequence of events may aid in the diagnosis and mangement of future cases.

TABLE I. COURSE OF PATIENTS SURVIVING 10 HOURS AFTER INJURY

	NUMBER OF CASES	CHRONIC	PROGRESSIVE	SURGICAL CURE	DEATH AFTER SURGERY	RUPTURE
Bradford and Johnston[6]	1					5 wk.
Bahnson[7]	1			1		
Corbitt[8]	1					20 hr.
Eiseman and Rainer[9]	6	2	1	1	1	9 da.
Forbes[10]	1					30 hr.
Goyette et al.[11]	3	2			1	
Hardin et al.[12]	1				1	
Henning and Agmar[13]	1					48 hr.
Hollingsworth et al.[14]	4	2	1	1		
Kuhn[15]	1					10 da.
Rice and Wittstruck[16]	1					5 wk.
Sarot and Lazzaieni[17]	1			1		
Steinberg[18]	5	4			1	
Storey et al.[19]	2			1		12 da.
Stranahan et al.[20]	1			1		
Strassman[5]	4					(4) 12 and 18 hr.
Ware et al.[21]	1				1	
Wyman[22]	3					(3) 11 hr.; 15 hr.; 8 da.
Zehnder[23]	1					4½ da.
Totals	39	10	2	6	5	16

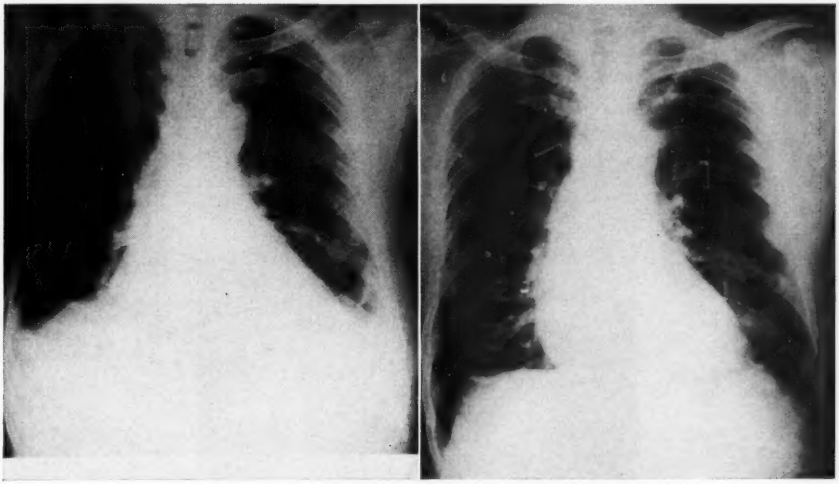
CASE REPORT

W. R., a 48-year-old man, was struck by a truck on Feb. 28, 1958. On admission to the hospital he was in extreme respiratory distress. A roentgenogram of the chest confirmed the clinical impression of multiple rib fractures and a bilateral hemothorax. Thoracentesis and supportive therapy relieved respiratory distress and blood pressure was maintained at 150/80 mm. Hg.

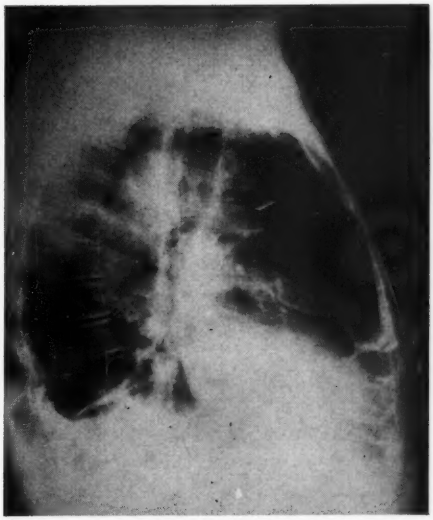
Ten days following injury the patient developed an episode of severe right chest and substernal pain accompanied by dyspnea, hyperpnea, and sweating. At this time the blood pressure was recorded as 220/100 mm. Hg. The electrocardiogram remained essentially unchanged throughout this period. Episodic pain recurred almost daily and alternating auricular fibrillation and flutter with a 2:1 block developed on the twentieth hospital day.

The patient was discharged on the thirty-first hospital day. Although digitalized he was readmitted 8 days later in acute left ventricular failure. The patient responded promptly to oxygen, diuretic drugs, and an increased dosage of digitalis. Arterial tension in both arms was recorded as 240/80 mm. Hg. A chest roentgenogram made 41 days after the injury now showed a double contour enlargement in the region of the aortic arch which suggested aneurysmal formation (Fig. 1). Chest pain and cardiac failure recurred and the patient was transferred to Presbyterian Hospital on April 28, 1958.

On admission the patient was dyspneic, orthopneic, and cyanotic, with a rapid irregular pulse. Arterial pressure in the right arm was 220/80, in the left arm 240/80 mm. Hg. Carotid pulses were equal to palpation. The blood pressure was recorded as 90/0 mm. Hg in both lower extremities and pulsations in the abdominal aorta could not be felt. The heart was enlarged to the anterior axillary line and a soft systolic murmur could be heard over



A. *B.*



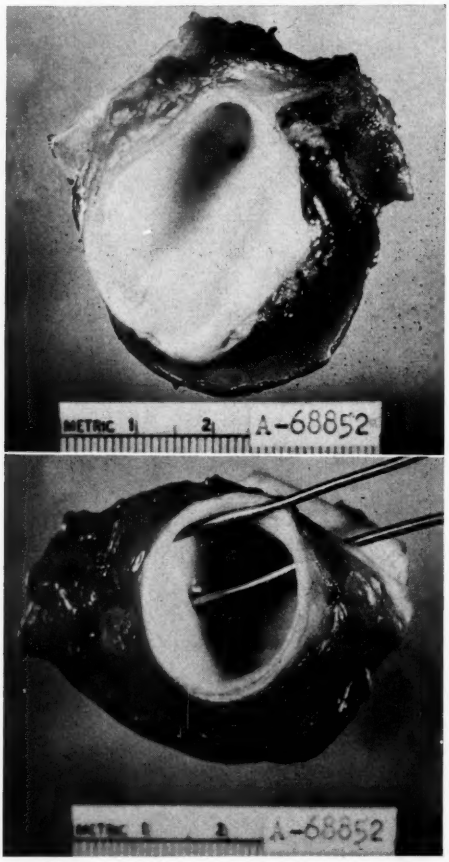
C.

Fig. 1.—*A*, Roentgenogram of the chest taken 2 weeks following injury shows evidence of multiple rib fractures and some widening of the mediastinum.

B, Subsequent x-ray studies 2 months following injury clearly demonstrated the prominent aorta arch with a double contour.

C, The lateral view shows the aneurysm arising in the proximal descending aorta.

the left chest anteriorly and posteriorly. The patient was placed on a strict cardiac regimen and signs and symptoms of cardiac failure resolved within 48 hours after admission. On May 14, an angiocardiogram was performed in two projections which confirmed the conventional roentgenographic appearance of an aneurysmal dilatation of the aorta just beyond the origin of the left subclavian artery.



A.

B.

Fig. 2.—*A*, The specimen shows the hematoma sac as viewed from the proximal end of the aortic segment.

B, An intact aortic wall is seen distally. Microscopically the hematoma separated the adventitia from the media with infarction noted in the outer two thirds of the media.

On May 20, approximately 3 months following injury, exploratory left thoracotomy was performed. An aneurysmal dilatation of the thoracic aorta was noted just distal to the left subclavian artery, measuring approximately 6 by 8 by 8 cm. Excision of the aneurysm was possible during partial perfusion of the distal aorta by a left atrium to left femoral artery bypass with a Sigmamotor pump.[24] A perfusion rate of 2,200 c.c. per minute was required to control proximal aortic hypertension. A preclotted crimped Dacron prosthesis* was inserted. On the day following surgery, the patient's blood pressure was 130/80 mm. Hg in

*Ethigraft available from Ethicon Inc., Somerville, N. J.

all extremities. The postoperative course was uneventful except for an episode of auricular fibrillation occurring on the second postoperative day which responded to increasing doses of digitalis. Since discharge the patient has remained normotensive and is well 1 year following surgery.

The pathologic specimen (Fig. 2) showed the large hematoma space outside the aortic lumen. The hematoma presented outside the media of the aortic wall microscopically, which probably explains why the dissection did not progress along the aorta as occurred in the case reported by Rice[16] of a pregnant woman at term, following chest injury. The diagram in Fig. 3 shows the probable sequence of events following aortic tear with formation of the partially obstructing hematoma.

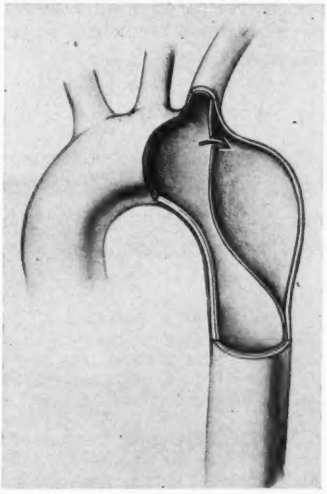


Fig. 3.—The schematic diagram illustrates the location and obstructing nature of the hematoma mass following the aortic wall dissection through the intimal tear.

DISCUSSION

The recent publications of Steinberg[18] and others[9] have raised a question as to the advisability of operating on a patient simply because the roentgenographic diagnosis of post-traumatic aneurysm is made. If observation proves to be an accepted form of clinical management, then a recognition of changing hemodynamics in the peripheral vascular system may be significant evidence of active bleeding and impending disaster following chest injury, as is well recognized in dissecting aneurysms. It is quite possible that the sudden development of hypertension proximal to an aortic hematoma may be a cause of sudden rupture late in the course of the aneurysm. Such a sequence of events is suggested in Case 3 reported by Eiseman,[9] although blood pressures were not reported. The patient developed a left hemothorax on the ninth post-injury day. Two hours following this he complained of numbness in his feet and femoral pulses disappeared. The patient suddenly then went into shock and subsequently died immediately after resection of a ruptured aneurysm of the thoracic aorta.

It is apparent that when rupture occurs, attempts at surgical correction have been associated with a high mortality. With the present-day use of atrial-femoral bypass, resection of aneurysms of the descending aorta can be carried out with a mortality of approximately 19 per cent,[25] as compared to 27 to 50 per cent using hypothermia or external shunts. There seems then little reason for delaying early surgical excision of an acute traumatic aneurysm or of a chronic symptomatic lesion, once the diagnosis has been established. Observation may be justified in the chronic, stable, calcified aneurysms if careful follow-up is available. Careful repeated records of peripheral pulses, particularly the femoral pulses, in patients following chest injury may give valuable information in the diagnosis and management of a traumatic aneurysm, and indeed may be an early sign heralding disaster.

SUMMARY

1. A case of post-traumatic thoracic aortic aneurysm has been described which presented a hemodynamic picture simulating coarctation of the aorta.

2. A careful apprasial of peripheral pulses in patients following chest injury may give valuable information in establishing a course of management.

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AN IMPROVED CAVAL CATHETER FOR CARDIAC BYPASS

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CAVAL CATHETERS must be very accurately placed in order to achieve free venous return. During the course of a long perfusion they will often shift out of position, especially if there is considerable manipulation. Moreover, the usual fixation of the catheter to the atrial appendage does not give adequate immobilization of the catheter tip.

Bardic venous catheters are firmly tied with a loop of umbilical tape, before autoclaving (see figure). After cooling, a permanent circumferential groove will be present, which will not significantly encroach on the catheter lumen. This

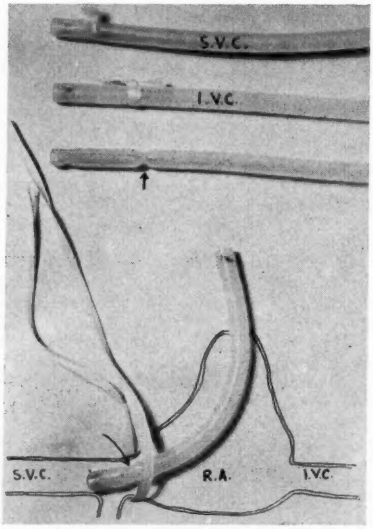

Fig. 1.

groove is then engaged by the caval tape when total bypass begins. Perhaps it is preferable to pass the caval tape around the vena cava *twice*, to give complete fixation of the catheter tip. The catheter tip is then firmly anchored in accurate position, regardless of subsequent manipulation of the heart and catheters.

This modification has been especially useful in the superior caval type of atrial defect, in which accurate position of the catheter tip is so essential. It is also useful in septum primum defects, in which considerable traction may be applied to the catheters.

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Announcements

THE AMERICAN ASSOCIATION FOR THORACIC SURGERY

Notice of Annual Meeting

The Forty-first Annual Meeting of The American Association for Thoracic Surgery will be held April 24, 25, and 26, 1961, in Philadelphia, Pennsylvania. Headquarters will be the Sheraton Hotel.

Requests for Hotel Reservations

These should be mailed directly to Mr. Brian Kirby, Reservation Manager, Sheraton Hotel, Philadelphia 3, Pennsylvania. Please mention this Association, the type of accommodation desired, the date, and approximate hour of arrival and departure. If accommodations are desired elsewhere please communicate directly with the hotel of your choice.

Material for the Program

SCIENTIFIC PAPERS.—Abstracts of all papers proposed for presentation at the 1961 meeting *must be received on or before* **November 15, 1960,** otherwise they will not be considered by the Program Committee. These should be labeled "For Thoracic Surgery Forum" or "For Regular Program" depending upon the nature of the subject matter, in the same manner as in previous years. They should contain from 200 to 250 words that accurately reflect the content of the completed paper.

Six, repeat, six clearly legible copies of *each* abstract must be sent to Miss Ada Hanvey, Administrative Assistant, The American Association for Thoracic Surgery, 308 Carondelet Building, 7730 Carondelet Avenue, St. Louis (Clayton) 5, Missouri.

Essayists selected for the program are reminded that papers presented at the meeting *must* be handed to the secretary *immediately* after their presentation. If they are not ready at that time there is a chance that they will not be published in THE JOURNAL OF THORACIC AND CARDIOVASCULAR SURGERY.

Applications for Membership

Applications for Associate Membership in the Association must be received by the Membership Committee *not later than* **November 15, 1960,** otherwise the application will be deferred for consideration until the 1962 meeting.

Applicants must be sponsored by three Active or Senior Members of the Association. In addition to the signature on the application form, the sponsors will forward a *separate* letter concerning the applicant directly to:

Frank Gerbode, M.D.
Chairman of the Membership Committee
Presbyterian Medical Center
San Francisco 15, California

Sponsors are reminded that *new* letters of recommendation must be forwarded to the Chairman of the Membership Committee should their applicants be held over for reconsideration a *second year.*